ADVANCED PROCESS CONTROL
A new look at the old

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About Sigurd Skogestad

- 1955: Born in Norway
- 1978: MS (Siv.ing.) in chemical engineering at NTNU
- 1979-1983: Worked at Norsk Hydro co. (process simulation)
- 1987: PhD from Caltech (supervisor: Manfred Morari)
- 1987-present: Professor of chemical engineering at NTNU
- 1994-95: Visiting Professor UC Berkeley
- 2001-02: Visiting Professor UC Santa Barbara
- 1999-2009: Head of ChE Department, NTNU
- 2015-..: Director SUBPRO (Subsea research center at NTNU)

Non-professional interests:

- **mountain skiing (cross country)**
- **orienteering (running around with a map)**
- **grouse hunting**

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“The goal of my research is to develop simple yet rigorous methods to solve problems of engineering significance”

One example: SIMC PID tuning rules (Skogestad, JPC, 2003)
«Probably the best simple PID tuning rules in the world»

Outline

1. Optimal steady-state operation of a process plant
    - Control hieararchy
    - Active constraints
2. Alternatives for implementing optimal operation and switching between active constraints
    - Model predictive control (MPC)
    - Standard advanced (process) control elements (APC)
3. APC elements for switching between active constraints
    - MV-MV switching: Split range control ++
    - CV-CV switching: Selectors
    - CV-MV swithcing: Nothing
4. Examples
    - Temperature control in room with combined heating and cooling
    - Pressure/Flow control with Combined max and min selectors
    - Serial Process with optimal buffer management

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Control is about implementing optimal operation in practice

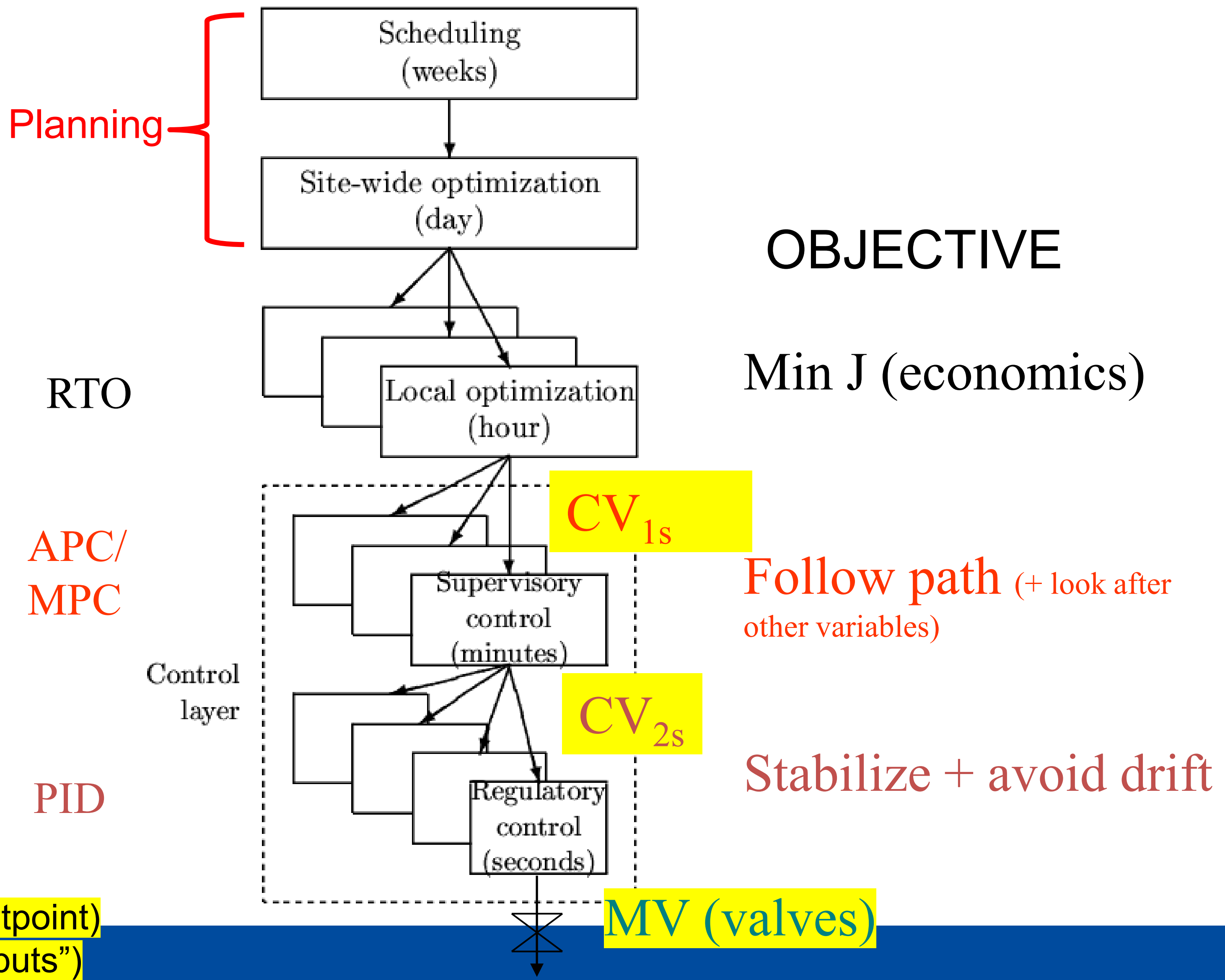
Main objectives control system:

1. **Economics**: Implementation of (near)-optimal operation
2. **Regulation:** Stable operation

ARE THESE OBJECTIVES CONFLICTING?

- Usually NOT
  - Different time scales
  - Stabilization doesn’t “use up” any degrees of freedom
    - Reference value (setpoint) available for layer above

Process control: Hierarchical structure



CV = controlled variable (with setpoint)
MV = manipulated variables ("inputs")

How we design a control system for a complete chemical plant?

- Where do we start?
- What should we control? and why?
- etc.
- etc.

Systematic design procedure

Start "top-down" with economics:

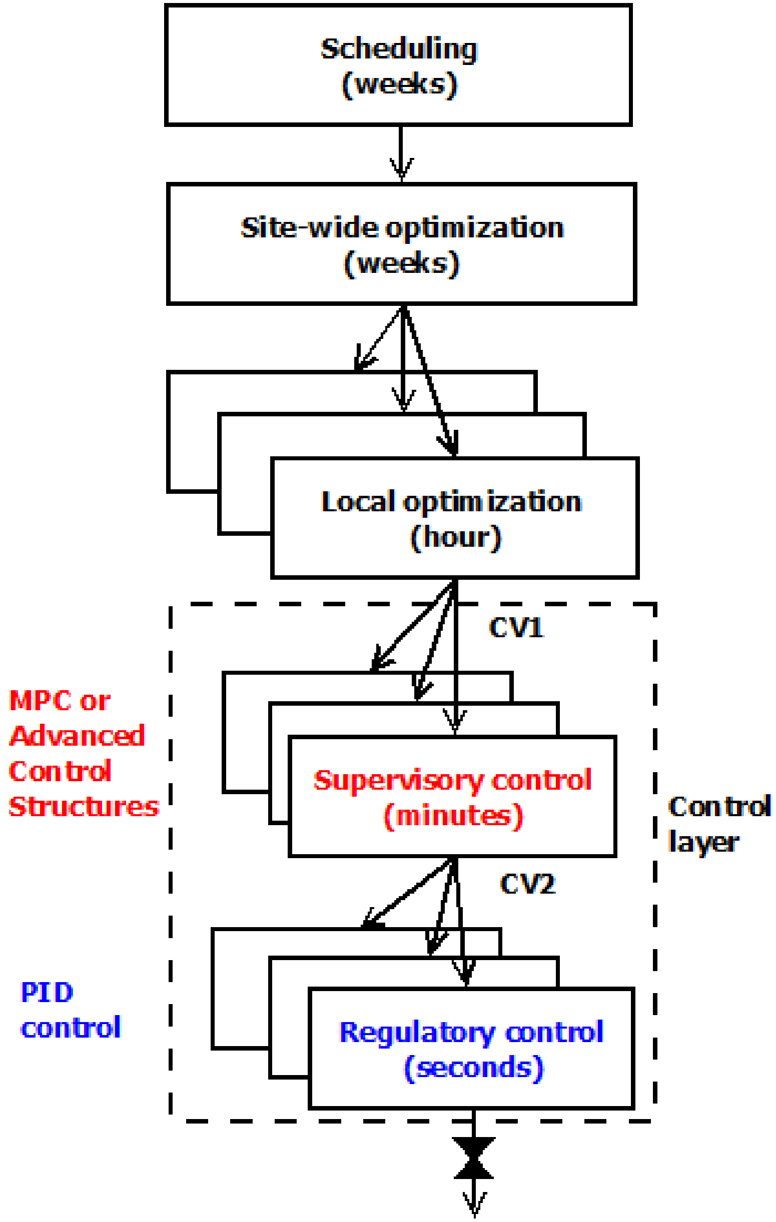
- Step 1: Define operational objectives and constraints
- Step 2: Optimize steady-state operation
- Step 3: Decide what to control (CV1)
- Step 4: Throughput manipulator (TPM) location

Then bottom-up:

- Step 5: Regulatory control (CV2)

Finally: Make link between "top-down" and "bottom up"

- Step 6: "Advanced/supervisory control" system



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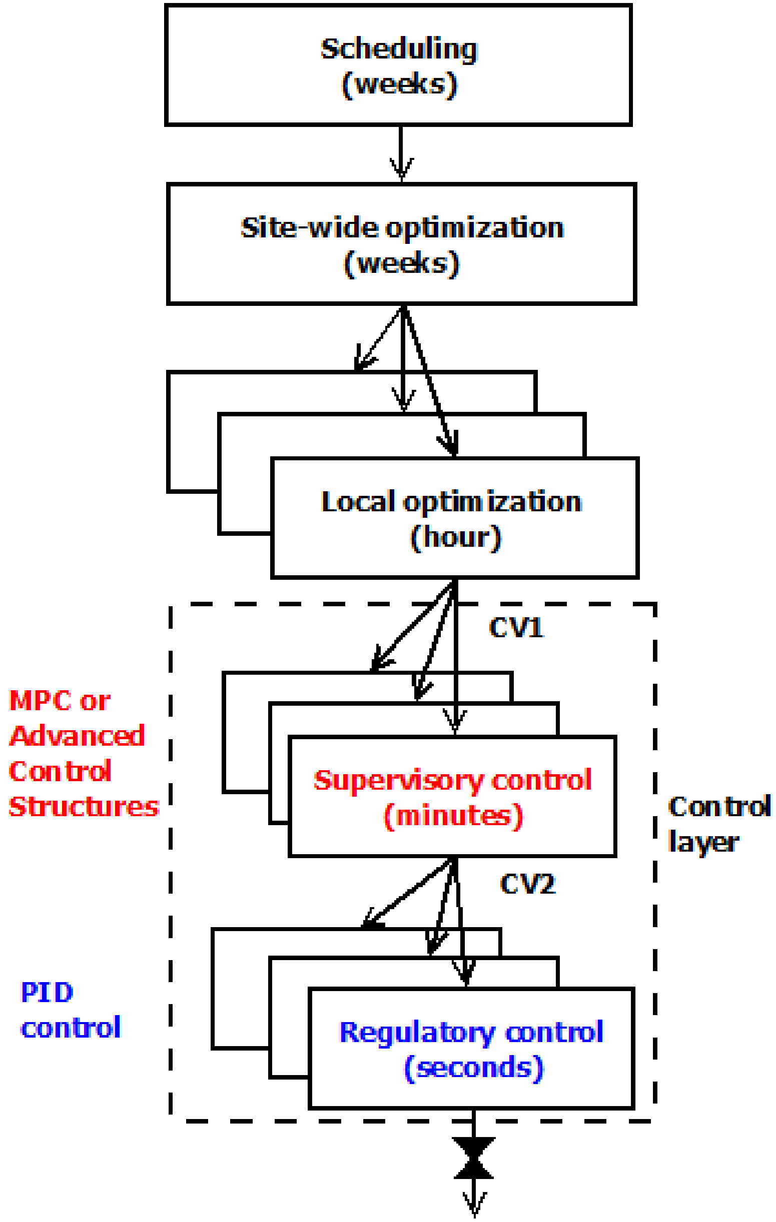
Advanced / Supervisory control layer

- Follow set points CV1s
- Switch between active constraints (CV1)
- Keep an eye on regulatory layer
  - Avoid saturation (constraints)

- **Alternatives:**
  - Model predictive control (MPC)
  - Standard advanced process control elements (APC)
    - Standard/Classical/Conventional



CV = controlled variable

Optimal steady-state operation

Optimize for expected disturbances (**d**)

$$\min_{\mathbf{u}} J(\mathbf{u},\mathbf{x},\mathbf{d})$$
$$s.t.$$
$$f(\mathbf{u},\mathbf{x},\mathbf{d}) = 0$$ ← Model equations
$$g(\mathbf{u},\mathbf{x},\mathbf{d}) \leq 0$$ ← Operational constraints

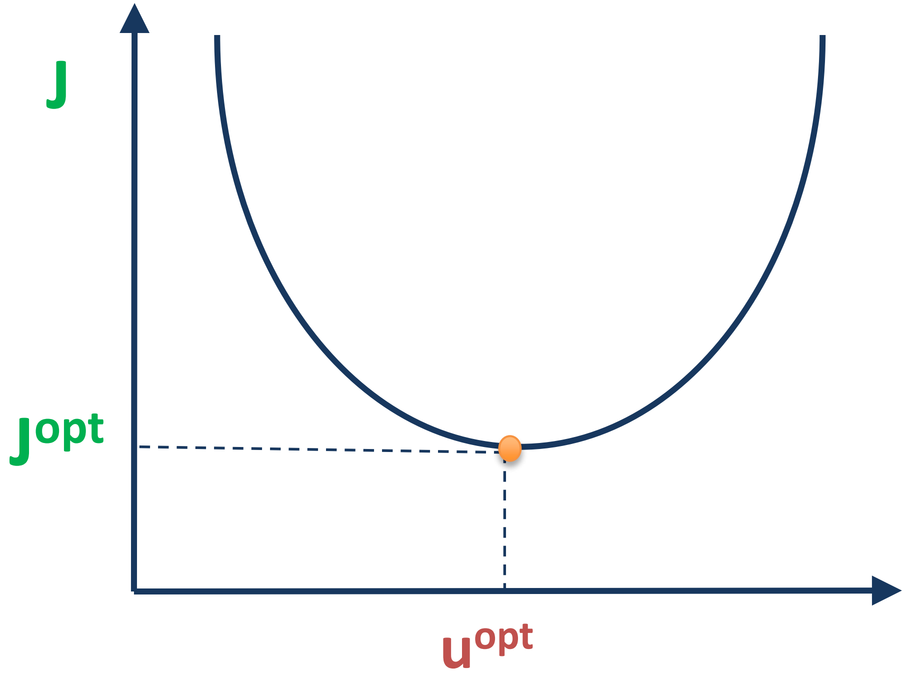
- We need a good model, usually steady-state.
- Optimization can be time consuming.

Main goal for control puposes: identify active constraint regions

- In many cases we can do this by feedback - without a model

Optimal operation (unconstrained)

Minimize cost J = J(**u**,**x**,**d**)



- **u** = degrees of freedom
- **x** = states (internal variables)
- **d** = disturbances

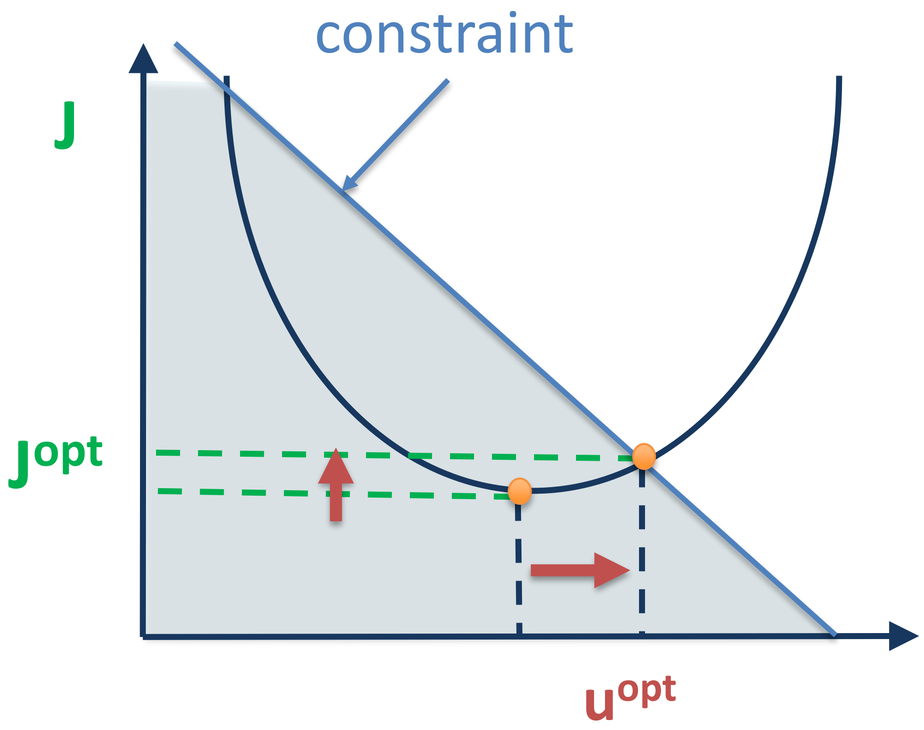
J = cost feed + cost energy – value of products

Optimal operation (constrained)

Minimize cost J = J(u,x,d)

Subject to satisfying constraints

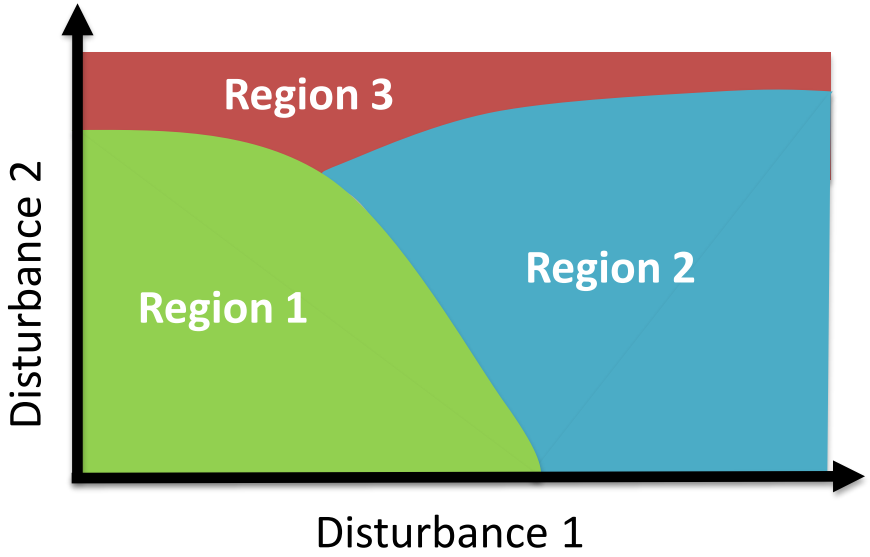
- u = degrees of freedom
- x = states (internal variables)
- d = disturbances



J = cost feed + cost energy – value of products

Active constraints

- **Active constraints:**
  - variables that should optimally be kept at their limiting value.
- **Active constraint region:**
  - region in the disturbance space defined by which constraints are active within it.



Optimal operation:
How switch between regions?

Control is about implementing optimal operation in practice

- Many cases: Optimal solution is constrained, but constraints change

→ Key is to control the active constraints and switch when needed

- **Alternatives:**
  - Model predictive control (MPC) (45 years old; Richalet)
    - Extensively studied in academia
  - Standard advanced process control elements (APC) (75 years old)
    - Hardly mentioned in academia

Model predictive control (MPC)

- Need dynamic model
- Implemented after some time of operation
- Handles constraints dynamically
- But changes in active constraints (steady state) is not as explicit as people think.

  Alt. 1. (Academic) Select weights in objective function

  - Indirect approach

  Alt. 2. (Industrial) Two-stage MPC with priority list

  - Steady-state feasibility part recomputes setpoints to meet active constraints
- Not all problems are easily formulated using MPC
  - In practice logic must often bed added

Alternative approach for handling changes in active constraints: Standard APC elements

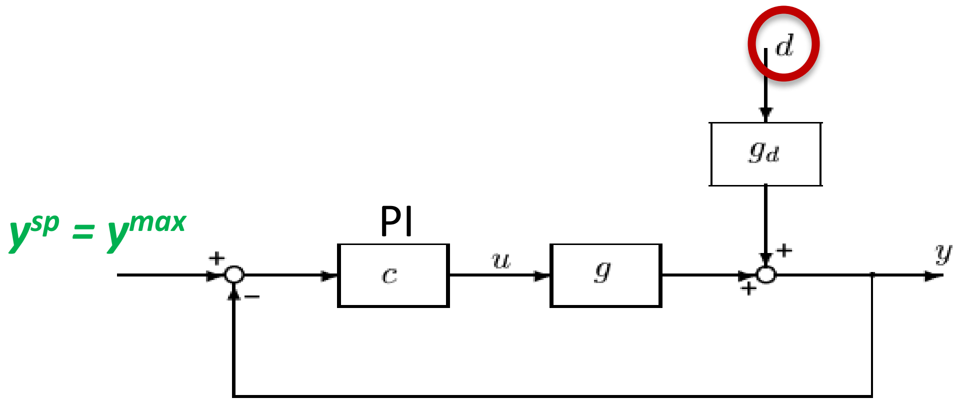
Some standard APC elements used for constraint switching:

- PI-controller
- Anti windup
- Max/min-Selectors
- Split range control
- Different setpoints
- Valve position control
- Other logic elements

Main limitation with standard APC is that we need to pair inputs (MVs) and outputs (CVs)

- Often an advantage as it gives explicit constraint handling
- But for some problems it may require complicated logic and MPC may be simpler

Optimization with PI-controller



max y

s.t. $y \leq y^{max}$

$u \leq u^{max}$

Example: Drive as fast as possible from A to B (u=power, y=speed, y^{max} = 130 km/h)

- **Optimal solution has two active constraint regions:**
  1. $y = y^{max}$ → **speed limit (d=smooth road)**
  2. $u = u^{max}$ → **max power (d=steep hill)**
- Note: Constraint on y satisfied with small input u (u^{max} no problem)
- **Solved with PI-controller («cruise control»)**
  - $y^{sp} = y^{max}$
  - Need anti-windup: I-action is off when $u=u^{max}$

s.t. = subject to

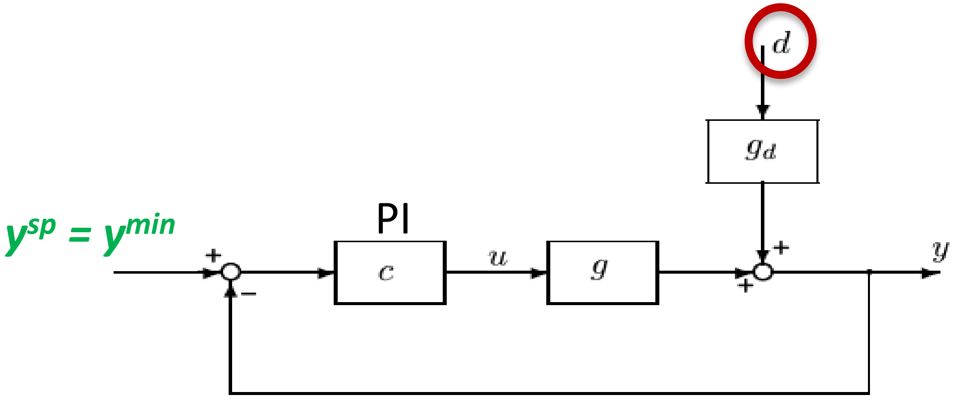
y = CV = controlled variable

Optimization with PI-controller

min u

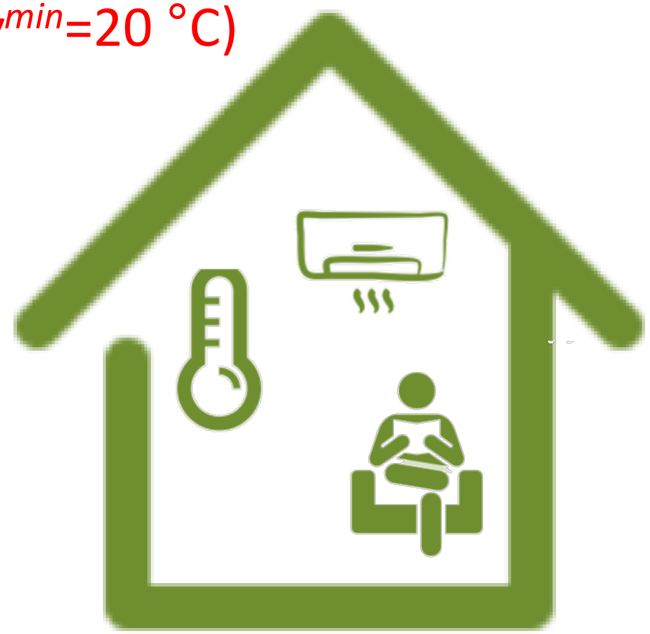
s.t. $y \geq y^{min}$

$u \geq u^{min} = 0$



Example Norway: Minimize heating cost (u=heating, y=temperature, y^{min}=20 °C)

- **Optimal solution has two active constraint regions:**
  1. $y = y^{min}$ → **minimum temperature (d=winter)**
  2. $u = u^{min}$ → **heating off (d=summer)**
- Note: Constraint on y satisfied with large input u (u^{min} no problem)
- **Solved with PI-controller**
  - $y^{sp} = y^{min}$
  - Need anti-windup: I-action is off when $u = u^{min}$



s.t. = subject to

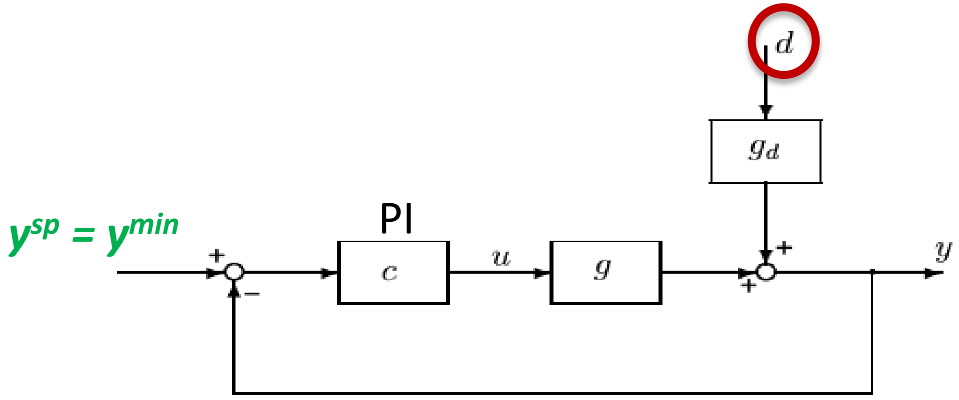
y = CV = controlled variable

Optimization with PI-controller

min u

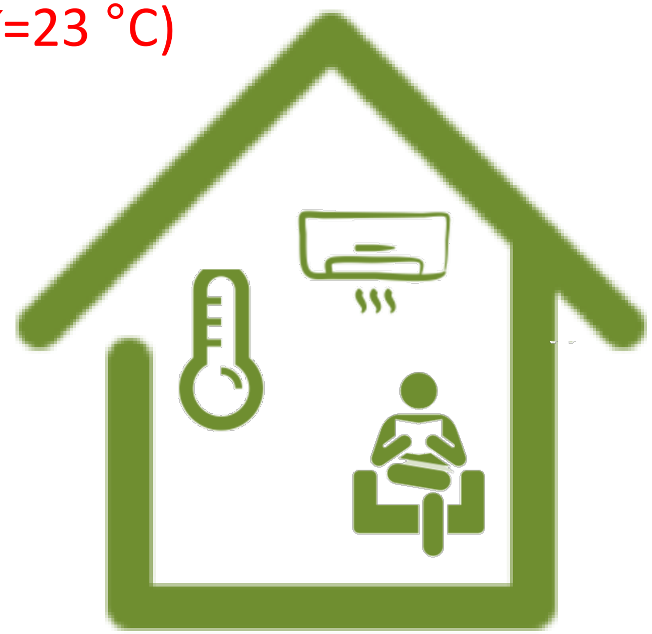
s.t. $y \leq y^{max}$

$u \geq u^{min} = 0$



Example Brazil: Minimize cooling cost (u=cooling, y=temperature, y^{max}=23 °C)

- **Optimal solution has two active constraint regions:**
  1. $y = y^{max}$ → **max temperature (d=summer)**
  2. $u = u^{min}$ → **cooling off (d=winter)**
- Note: Constraint on y satisfied with large input u (u^{min} no problem)
- **Solved with PI-controller**
  - $y^{sp} = y^{max}$
  - Need anti-windup: I-action is off when $u=u^{min}$

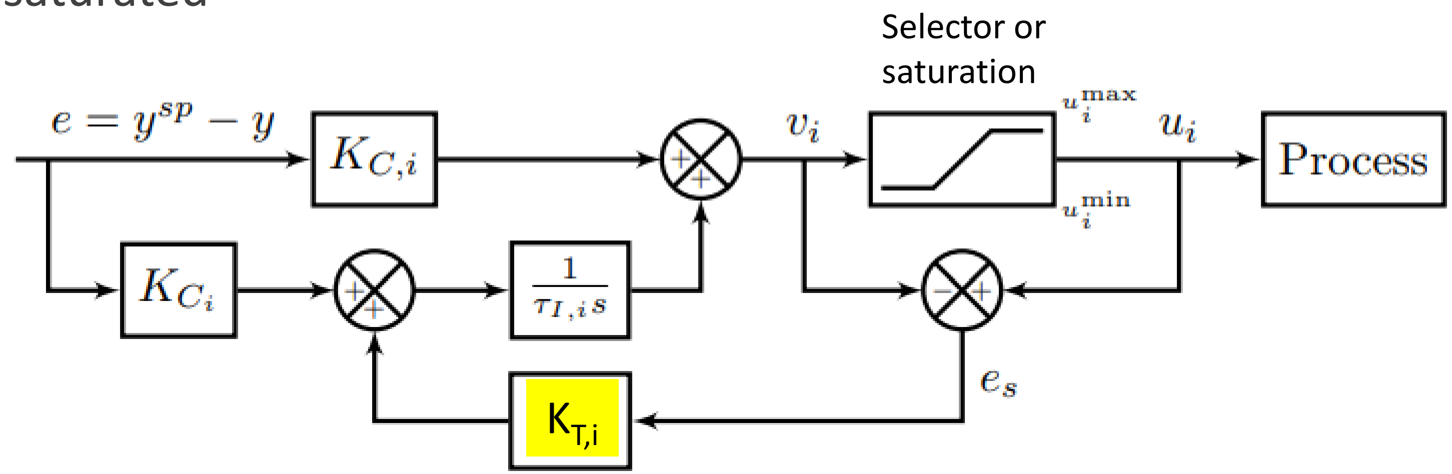


s.t. = subject to

y = CV = controlled variable

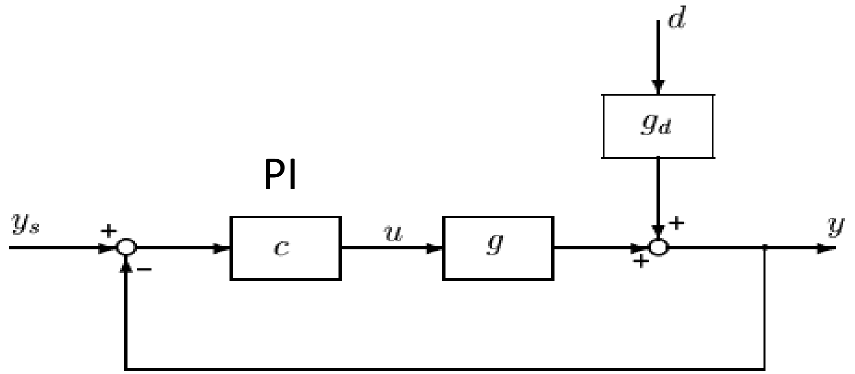
Anti-windup

- All the controllers shown need anti-windup to «stop integration» during periods when the control action (v_i) is not affecting the process:
  - Controller is disconnected (because of selector)
  - Physical MV u_i is saturated



Anti-windup using back-calculation. Typical choice for tracking constant, K_T=1

Optimization with PI-controller



All cases:

- Normal operation: $y=y^{sp}$
- When u (MV) reaches constraint: control of y (CV) is given up (and this is optimal)

Input saturation pairing rule:

- **«Pair MV that saturates with CV that can be given up»**

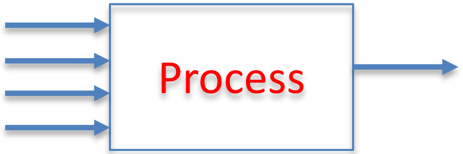
Constraints switching with standard APC

Three cases:

- MV-MV switching
  - One CV paired with many MVs (to cover whole range)
    1. Split range control
    2. Many controllers with different setpoints
    3. Valve position control
- CV-CV switching
  - Many CVs paired with one MV
    - Selectors
- CV-MV switching
  - CV paired with MV that may saturate
    1. Simple PI control is optimal if we follow «input saturation pairing rule»
    2. If we don't follow this rule:
       - Must combine MV-MV and CV-CV (selector)

* A. Reyes-Lua and S. Skogestad, «Systematic design of active constraint switching using classical advanced control structures», Ind.Eng.Chem.Res, Vol. 59, 2229-2241 (2020)

MV-MV switching



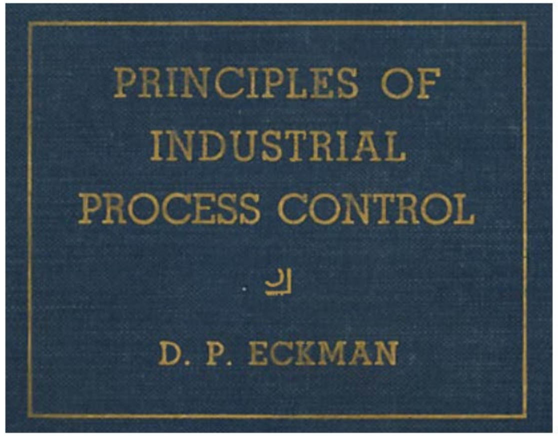
One CV paired with many MVs (to cover whole range).

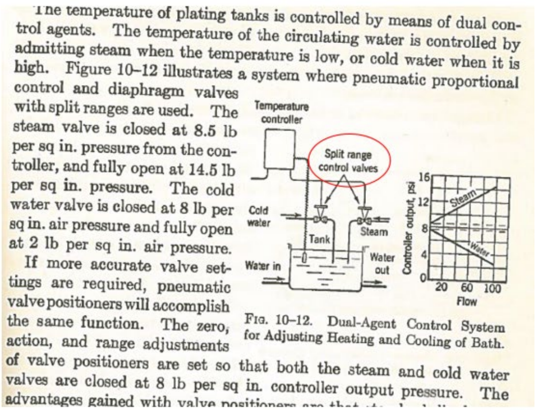
Want to use only MV at a time

Switching options:

1. Split range control
2. Many controllers with different setpoints
3. Valve position control

Eckman, D.P. (1945). Principles of industrial control, pp.204-207. John Wiley & Sons, New York.



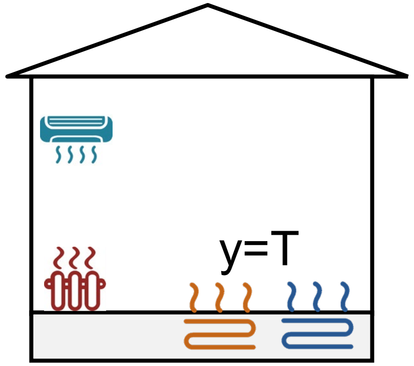


The temperature of plating tanks is controlled by means of dual control agents. The temperature of the circulating water is controlled by admitting steam when the temperature is low, or cold water when it is high. Figure 10–12 illustrates a system where pneumatic proportional control and diaphragm valves with split ranges are used. The steam valve is closed at 8.5 lb per sq in. pressure from the controller, and fully open at 14.5 lb per sq in. pressure. The cold water valve is closed at 8 lb per sq in. air pressure and fully open at 2 lb per sq in. air pressure.

If more accurate valve settings are required, pneumatic valve positioners will accomplish the same function. The zero, action, and range adjustments of valve positioners are set so that both the steam and cold water valves are closed at 8 lb per sq in. controller output pressure. The advantages gained with valve positioners are that ...

FIG. 10–12. Dual-Agent Control System for Adjusting Heating and Cooling of Bath.

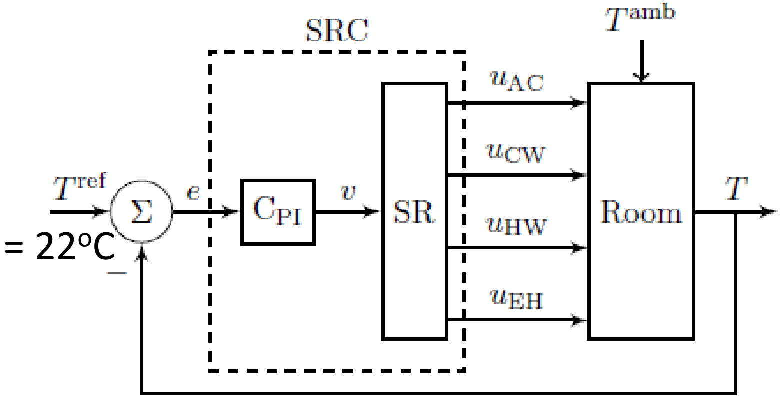
Example: Room heating with one CV (T) and 4 MVs

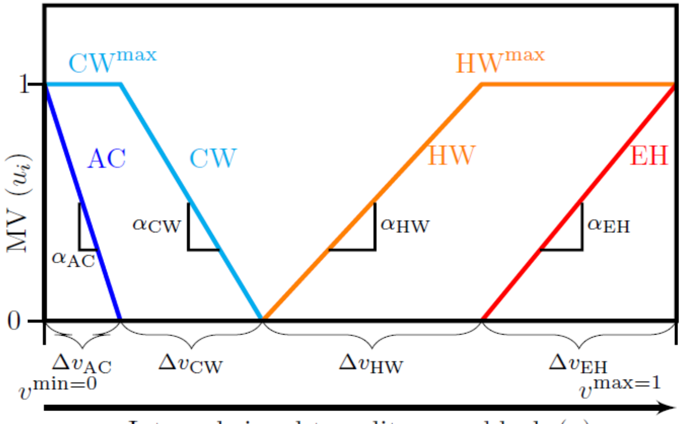


MVs (two for summer and two for winter):

1. AC (expensive cooling)
2. CW (cooling water, cheap)
3. HW (hot water, quite cheap)
4. Electric heat, EH (expensive)

Alt. 1 Split-range control (SRC).

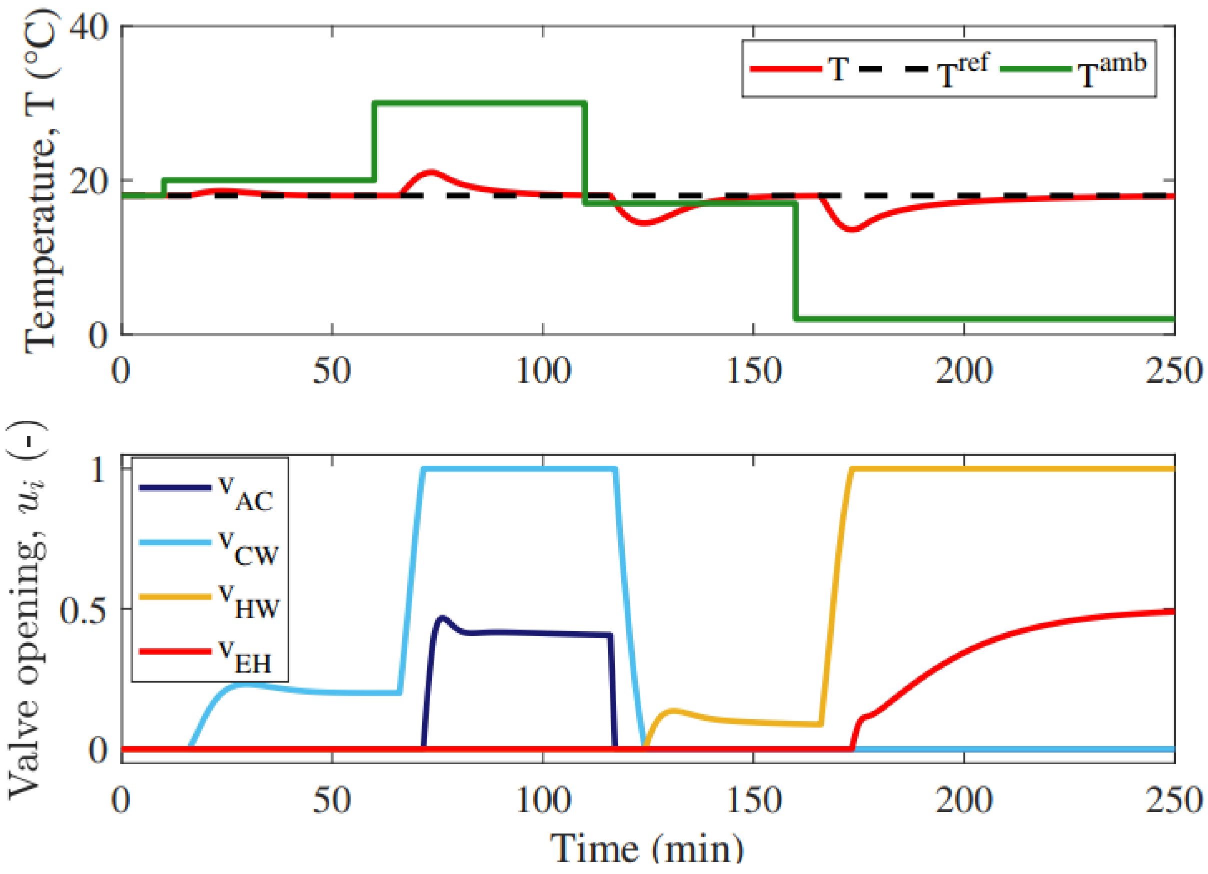




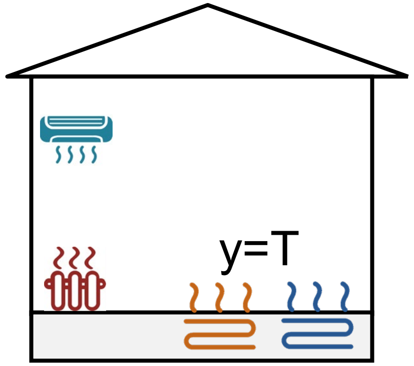
Note: may adjust the location of split (x-axis) to make loop gains equal.

Disadvantage SRC: 1. Must use same integral time for all MVs
2. Does not work well for cases where constraint values change

Alt. 1 Split-range control (SRC).



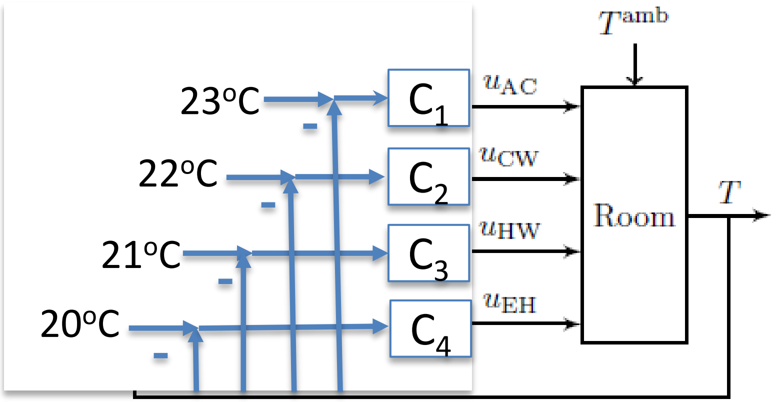
Example: Room heating with one CV (T) and 4 MVs



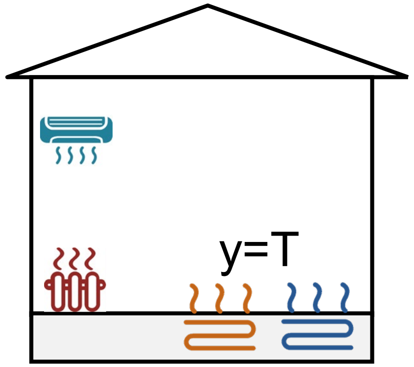
MVs (two for summer and two for winter):

1. AC (expensive cooling)
2. CW (cooling water, cheap)
3. HW (hot water, quite cheap)
4. Electric heat, EH (expensive)

Alt. 2. Multiple controllers with different setpoints



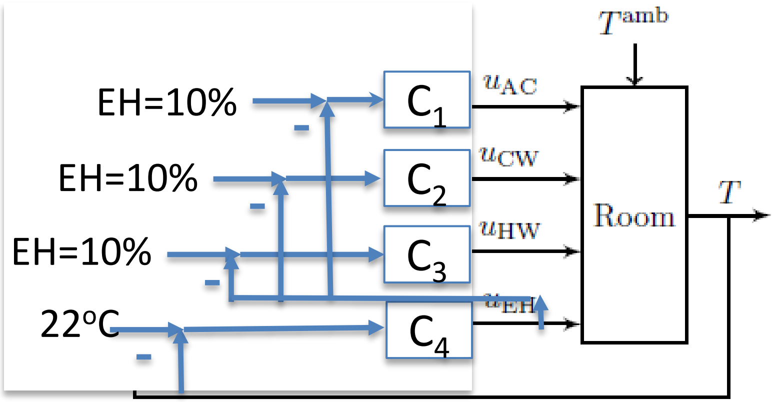
Example: Room heating with one CV (T) and 4 MVs



MVs (two for summer and two for winter):

1. AC (expensive cooling)
2. CW (cooling water, cheap)
3. HW (hot water, quite cheap)
4. Electric heat, EH (expensive)

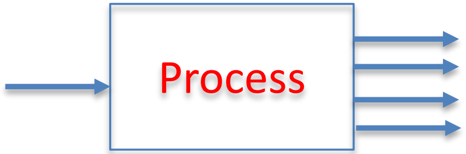
Alt. 3. Input resetting (Valve position control)



Summary MV-MV switching

- Use Alt.1 (split range control) for fixed MV ranges (max and min values)
  - Advantage: Easy to understand, because SR-block shows clearly sequence of MVs
- Use Alt. 2 (controllers for different setpoints) for cases where MV ranges vary
  - Advantage: Easier to implement than SRC and can have different controller tunings
  - Often preferred for CV-MV switching
- Use Alt. 3 (input resetting) for cases where CV (y) should always be controlled by same MV
  - Not so common
  - Gives some economic loss

CV-CV switching



Many CVs paired with one MV.

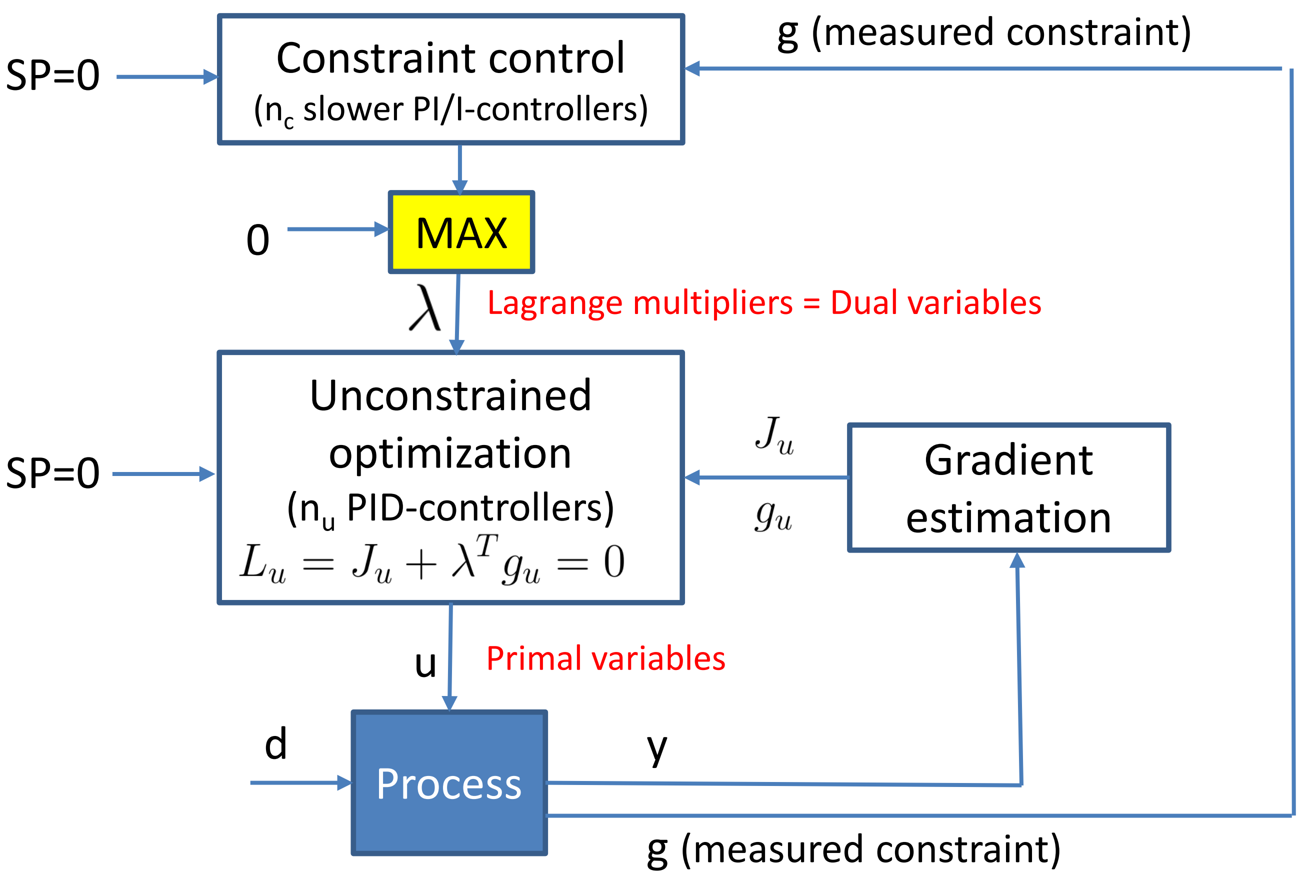
But only one CV controlled at a time.

Use: Max or Min selector

> = MAX = HS

< = MIN = LS

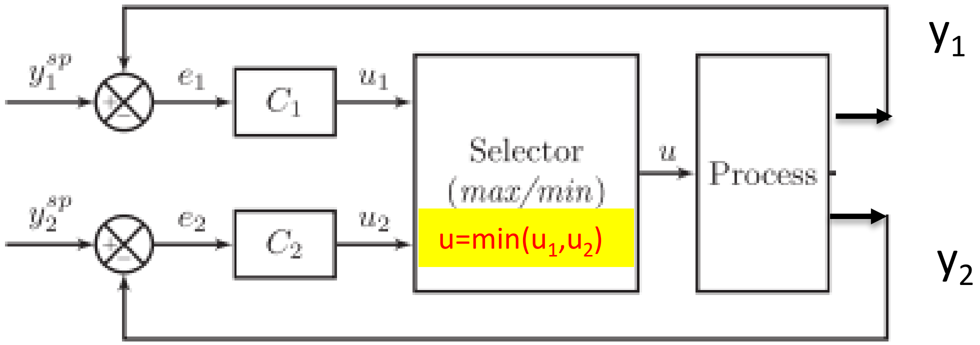
Selectors have basis in constrained optimization theory



«Primal-dual feedback control»

- Makes use of «dual decomposition» of constrained optimization
- Selector on dual variables λ
- Problem: Constraint control using dual variables is on slow time scale

CV-CV switching using selectors



- Sometimes called "override"
- Typical Example: Want to keep y1 at a setpoint,
    - but y2 (higher priority) must not exceed constraint.
    - With selector: When y2 reaches constraint, we give up control of y1.
  - Example: adaptive cruise control.
    - y1= speed limit, y2= distance (3s), Min-selector
- Selectors work well, but require pairing each constraint with a given input (not always possible)

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Design of selector structure

Rule 1 (max or min selector)

- Use max-selector for constraints that are satisfied with a large input
- Use min-selector for constraints that are satisfied with a small input

Rule 2 (order of max and min selectors):

- If need both max and min selector: Potential infeasibility
- Order does not matter if problem is feasible
- If infeasible: Put highest priority constraint at the end

"Systematic design of active constraint switching using selectors."
Dinesh Krishnamoorthy , Sigurd Skogestad. Computers & Chemical Engineering, Volume 143, (2020)

Maximize flow with pressure constraints

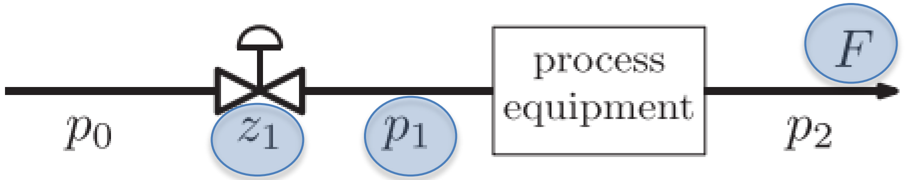


Fig. 6. Example 2: Flow through a pipe with one MV ($u = z_1$).

Optimization problem is:

$$\max_{z_1} F$$

s.t.

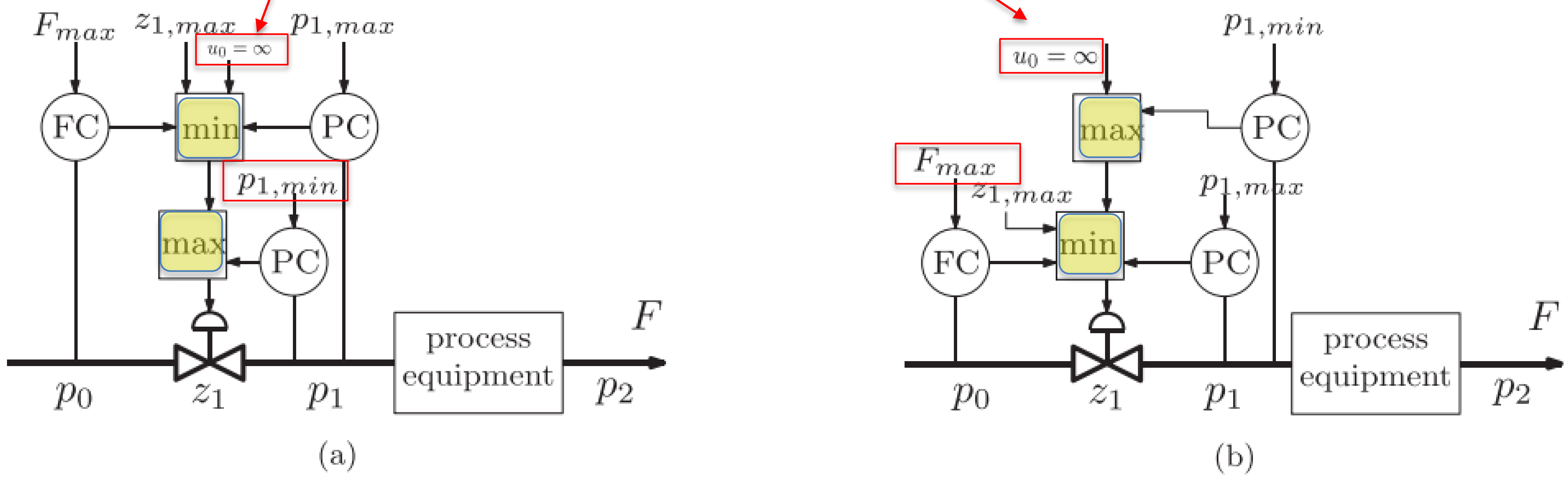
$$F \leqslant F_{max}$$
$$p_1 \leqslant p_{1,max}$$
$$p_1 \geqslant p_{1,min}$$
$$z_1 \leqslant z_{1,max} \qquad (15)$$

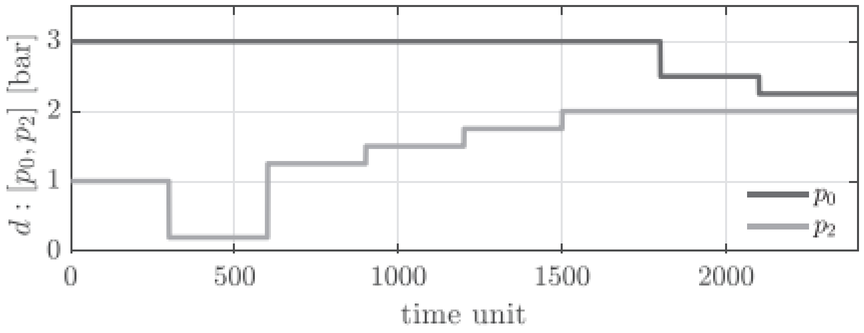
where $F_{max} = 10$ kg/s, $z_{1,max} = 1$, $p_{1,max} = 2.5$ bar, and $p_{1,min} = 1.5$ bar. Note that there are both max and min- constraints on p_1. De-

Input u = z_1
Want to maximize flow, J=-F:
Unconstrained: Optimal input is infinity:

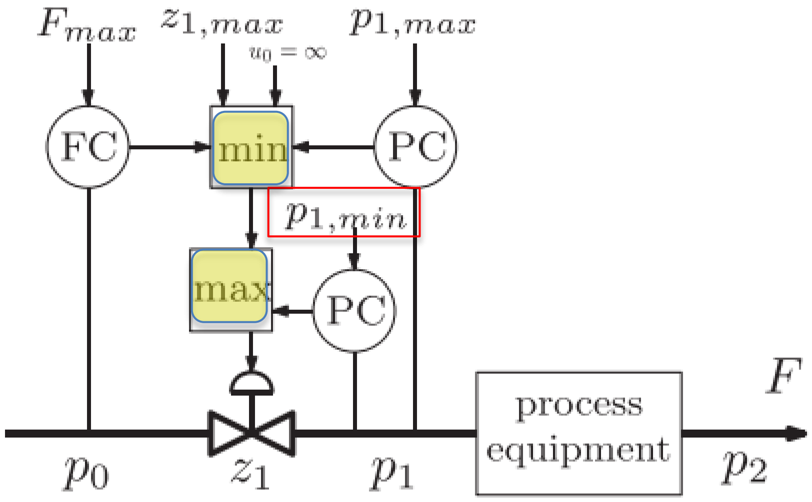
$$u_0 = \infty$$

Desired input u_0 without constraints (can be given up) into first selector block

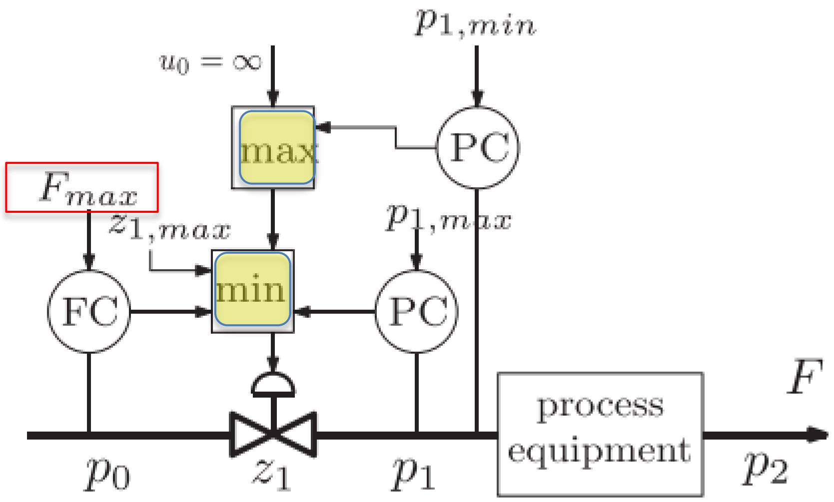




Disturbances in p_0 and p_2 (unmeasured)



(a)



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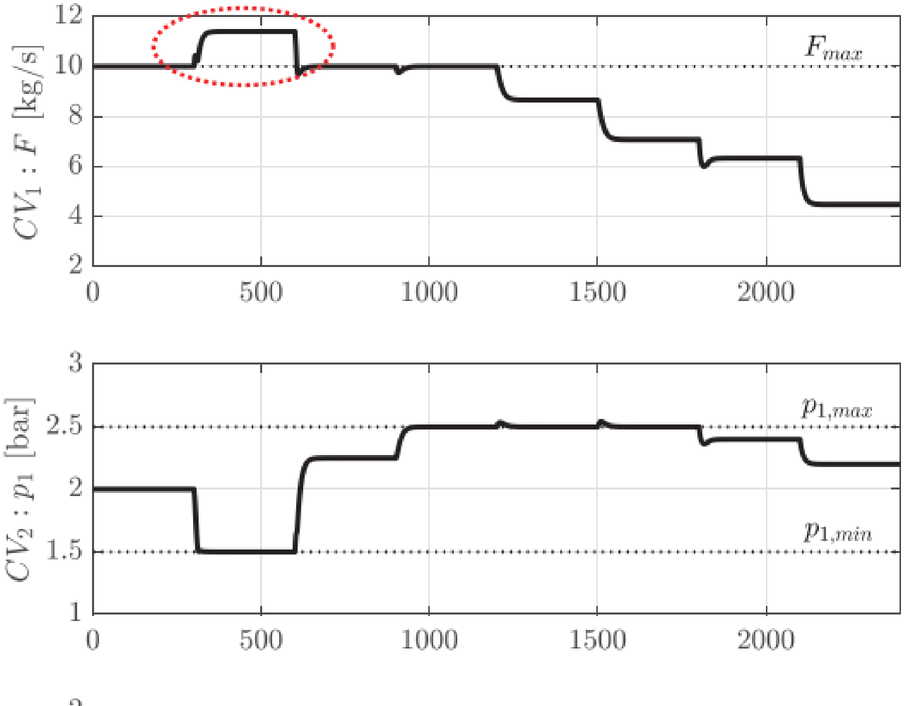

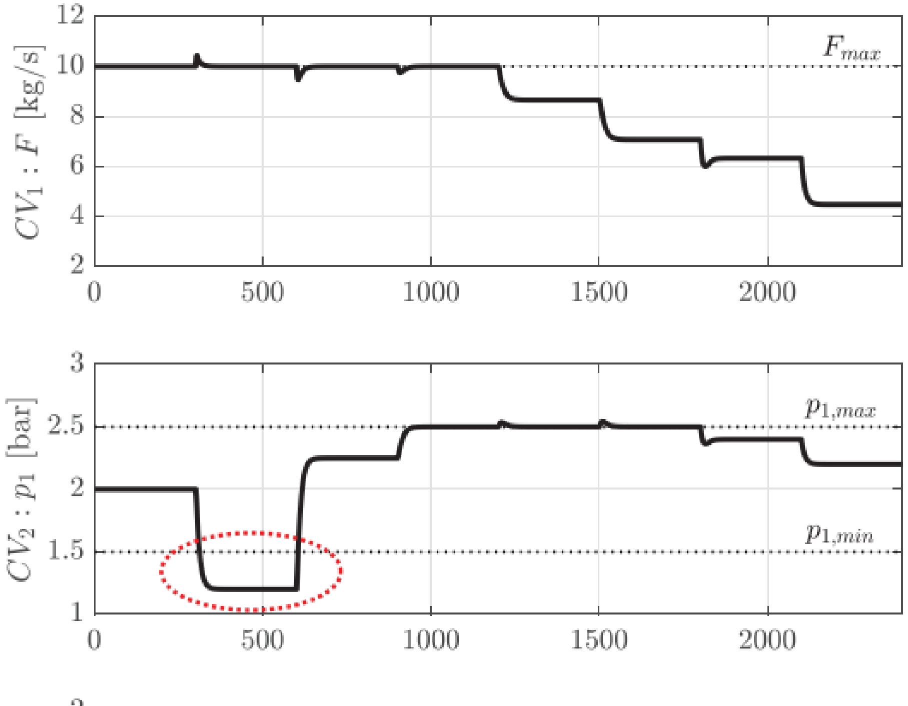

t>1800: u=zmax=1

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Challenges selectors

- Standard approach requires pairing of each active constraint with a single input
  - May not be possible in complex cases
- Stability analysis of switched systems is still an open problem
  - Undesired switching may be avoided in many ways:
    - Filtering of measurement
    - Tuning of anti-windup scheme
    - Minimum time between switching
    - Minimum input change

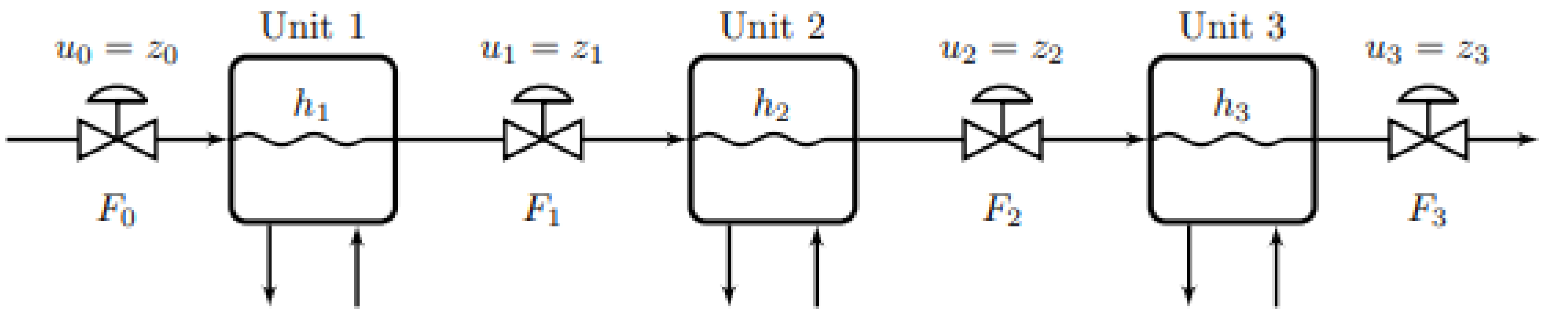
CV-MV switching

CVs paired with MV that may saturate

If we cannot follow «input saturation pairing rule» then we must combine

- MV-MV switching (Alt.2 Different setpoint usually best)
- CV-CV switching (selector)

Example. Inventory control for Serial process



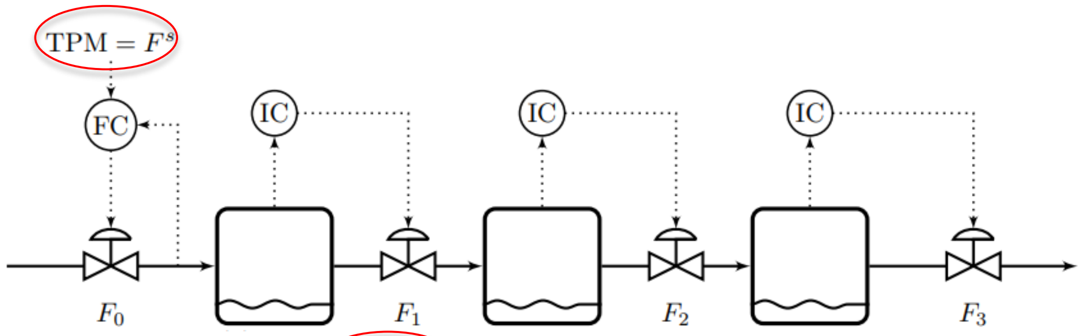
CVs: 3 inventories (levels) within min and max
MVs: 4 flows (valves)

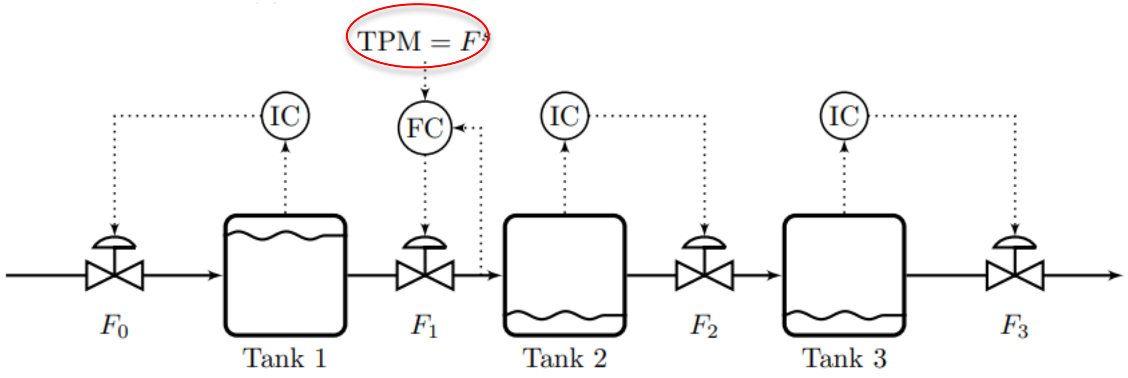
Objective (in addition to controlling levels): Maximize throughput (integrated over time)
-> one valve fully open or at bottleneck

How to control?
Need MPC?

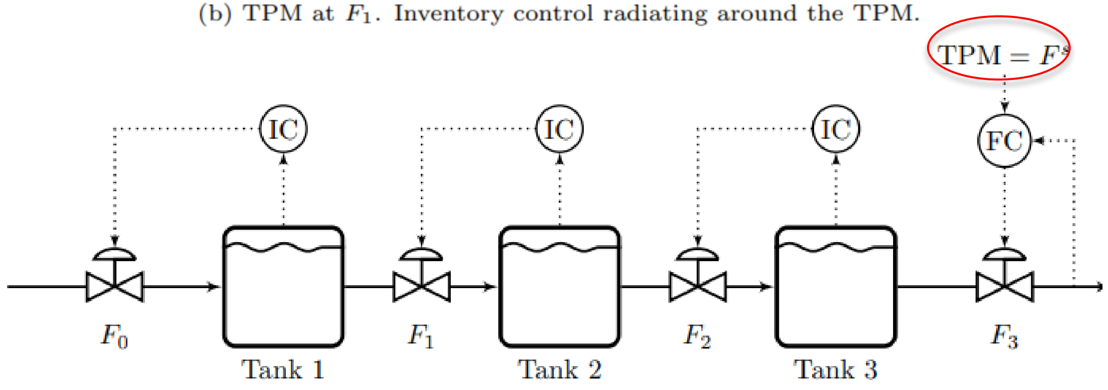
TPM = throughput manipulator
Typically at bottleneck («active constraint»)

Disturbances: Temporary bottelenecks (max-constraints) for F0, F1, F2 or F3





(b) TPM at F_1. Inventory control radiating around the TPM.

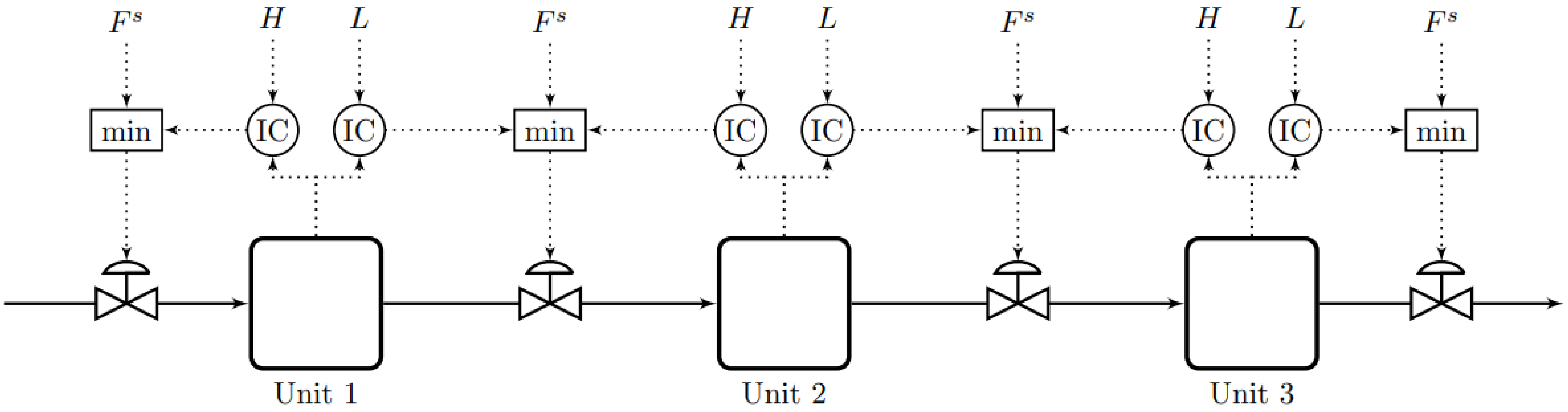


(d) TPM at F_3. Inventory control in direction opposite of flow.

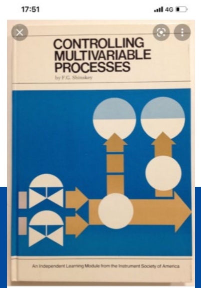
Example B. Very smart selector strategy: **Bidirectional inventory control**

Reconfigures automatically with optimal buffer management!!

Max flow:
$F^s=\infty$



F.G. Shinskey, «Controlling multivariable processes», ISA, 1981
C. Zotica, S. Skogestad and K. Forsman, Comp. Chem. Eng, 2021



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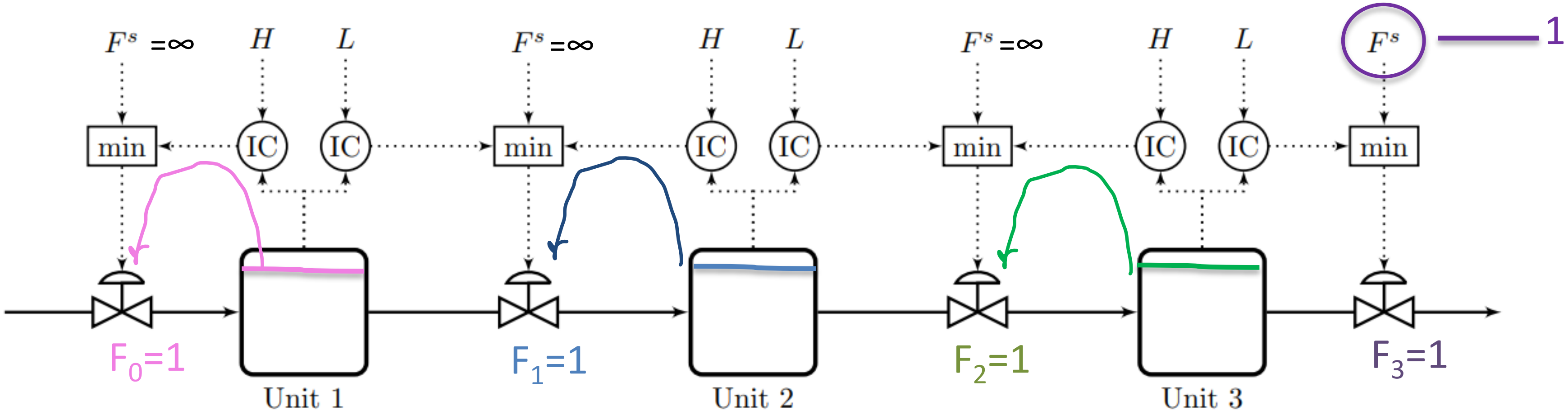
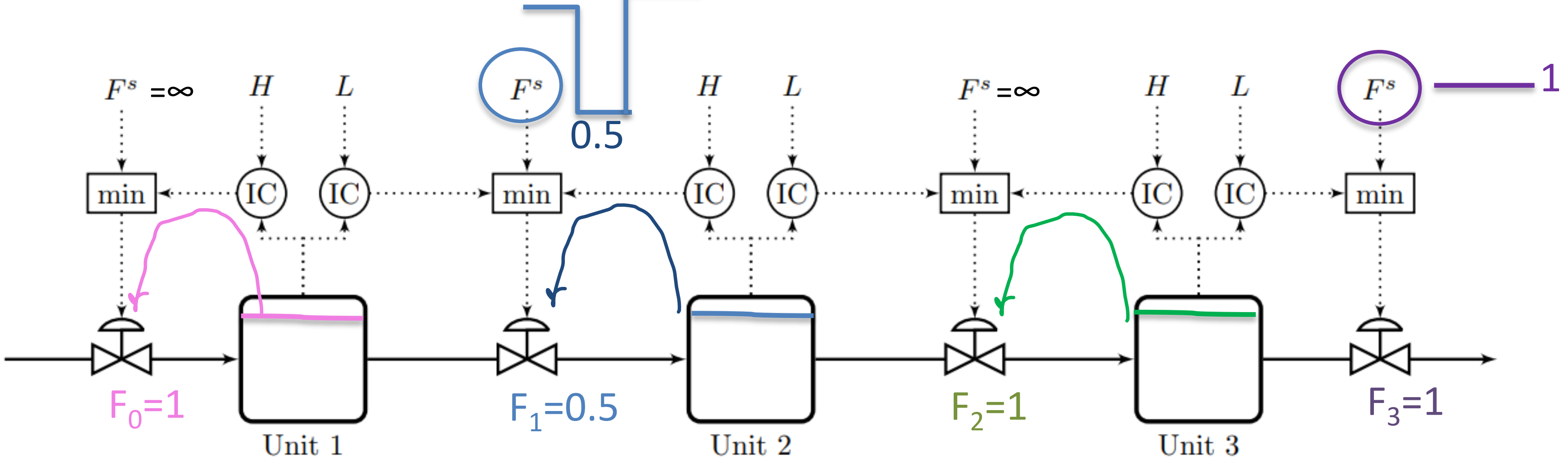


F^s =∞
H
L
min
IC
IC
F^s =∞
H
L
min
IC
IC
F^s =∞
H
L
min
IC
IC
F^s
1
min
F_0=1
Unit 1
F_1=1
Unit 2
F_2=1
Unit 3
F_3=1



F^s =∞
H
L
min
IC
IC
F^s
0.5
min
IC
IC
F^s =∞
H
L
min
IC
IC
F^s
1
min
F_0=1
Unit 1
F_1=0.5
Unit 2
F_2=1
Unit 3
F_3=1

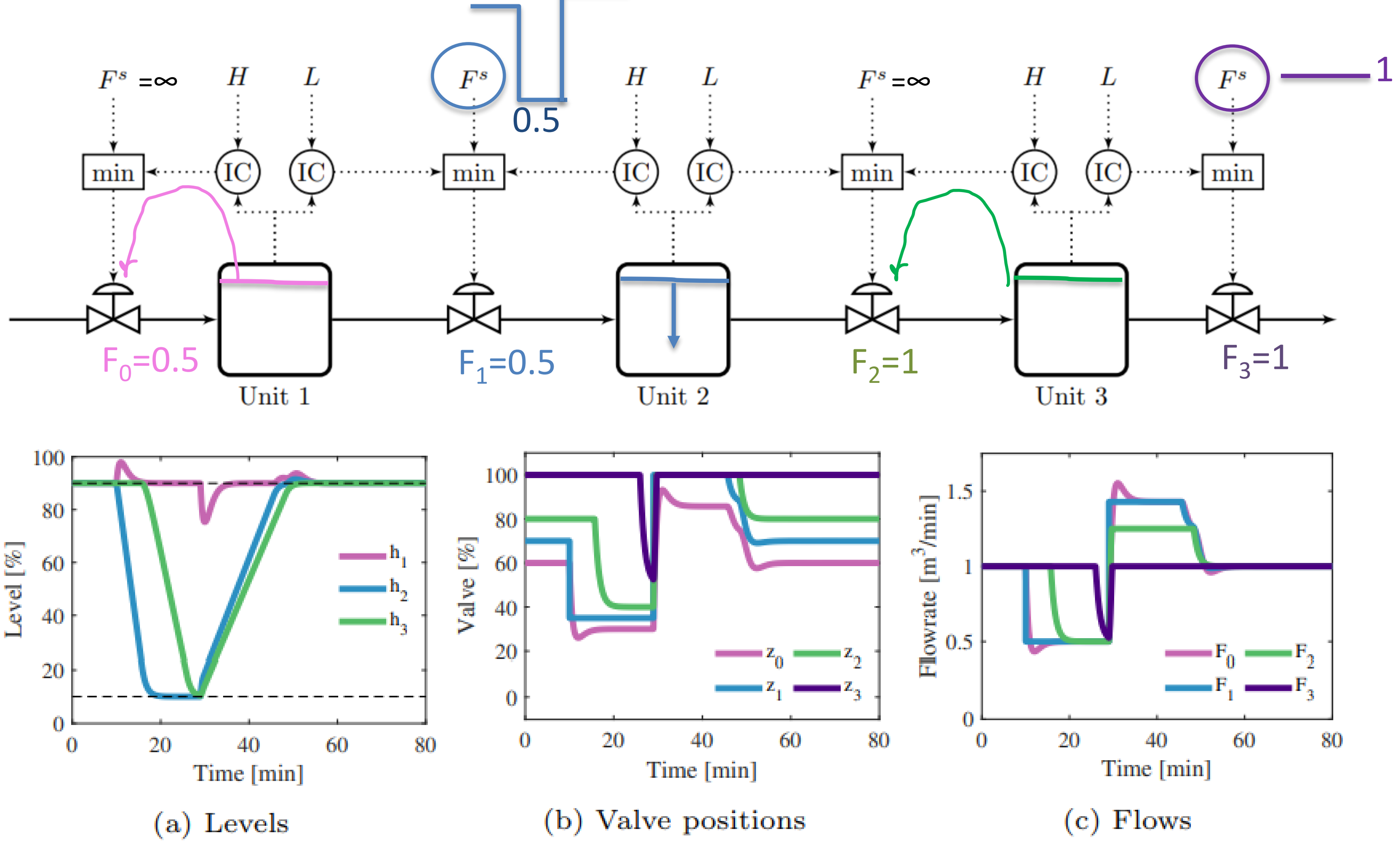


Figure 12: Simulation of a 19 min temporary bottleneck in flow F_1 for the control structures in Fig. 3d with the TPM downstream of the bottleneck.

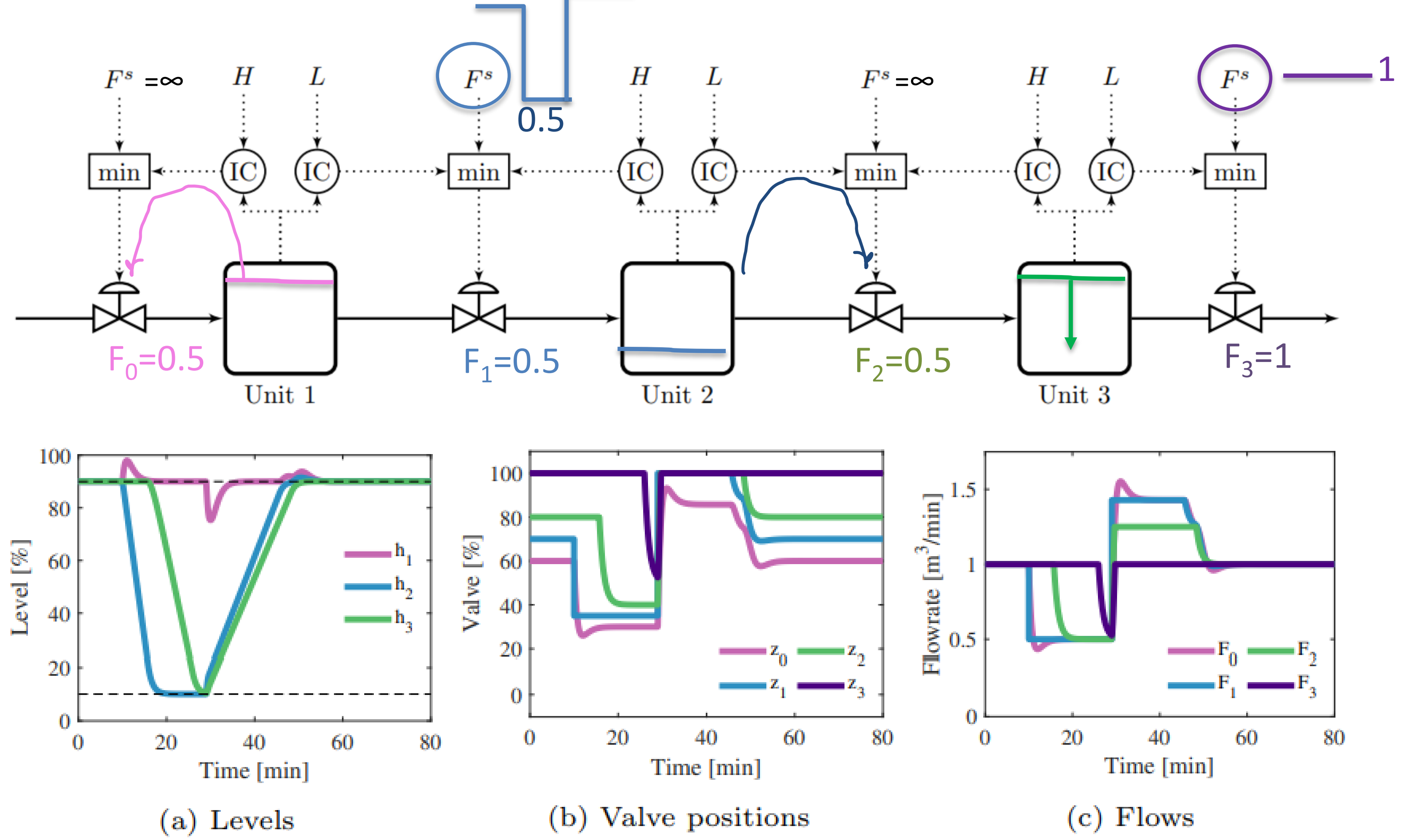
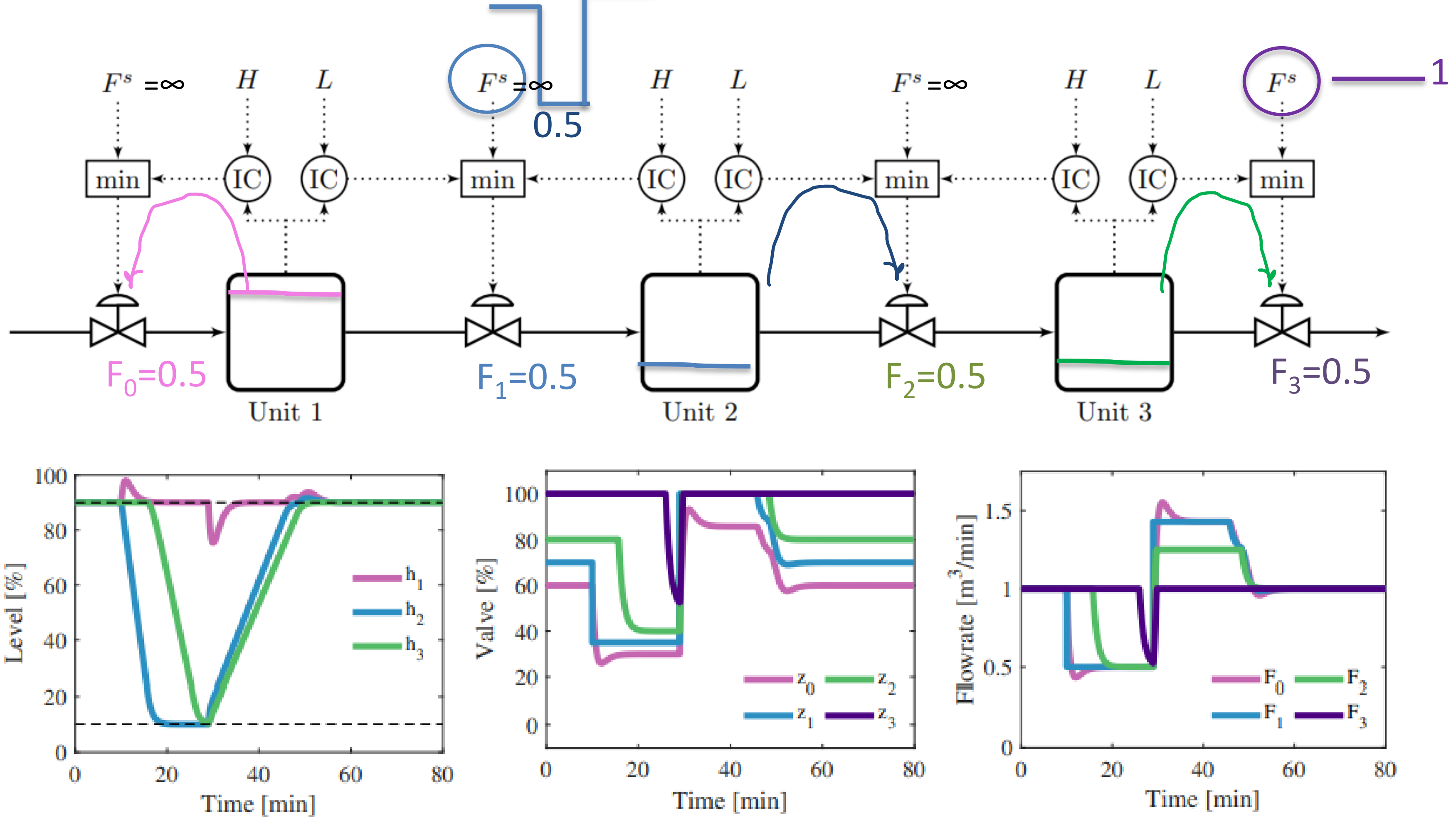


Figure 12: Simulation of a 19 min temporary bottleneck in flow F_1 for the control structures in Fig. 3d with the TPM downstream of the bottleneck.



(a) Levels (b) Valve positions (c) Flows

Figure 12: Simulation of a 19 min temporary bottleneck in flow F_1 for the control structures in Fig. 3d with the TPM downstream of the bottleneck.

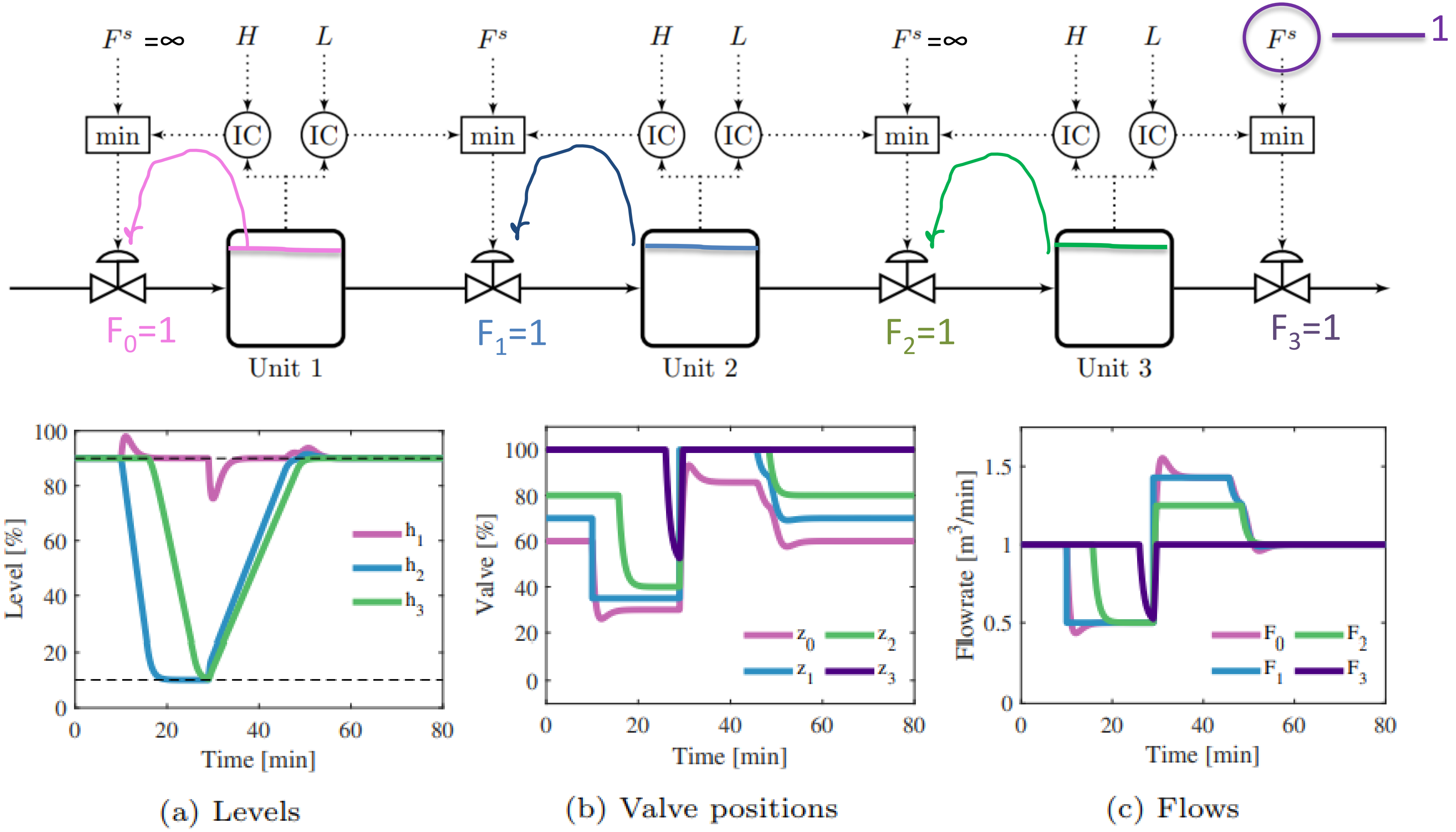


Figure 12: Simulation of a 19 min temporary bottleneck in flow F_1 for the control structures in Fig. 3d with the TPM downstream of the bottleneck.

Challenge: Can MPC be made to do his? Optimally reconfigure loops and find optimal buffer? I doubt it. We tried.

Important insight

- Many problems: Optimal steady-state solution always at constraints
- In this case optimization layer may not be needed
  - if we can identify the active constraints and control them using selectors

CV-MV switching. Optimal control of a cooler

Main control objective:

$y_1 = T_H = T_H^{sp} = 26.5C$

Secondary objective (can be given up)

$y_2 = F_H = F_H^{sp}$

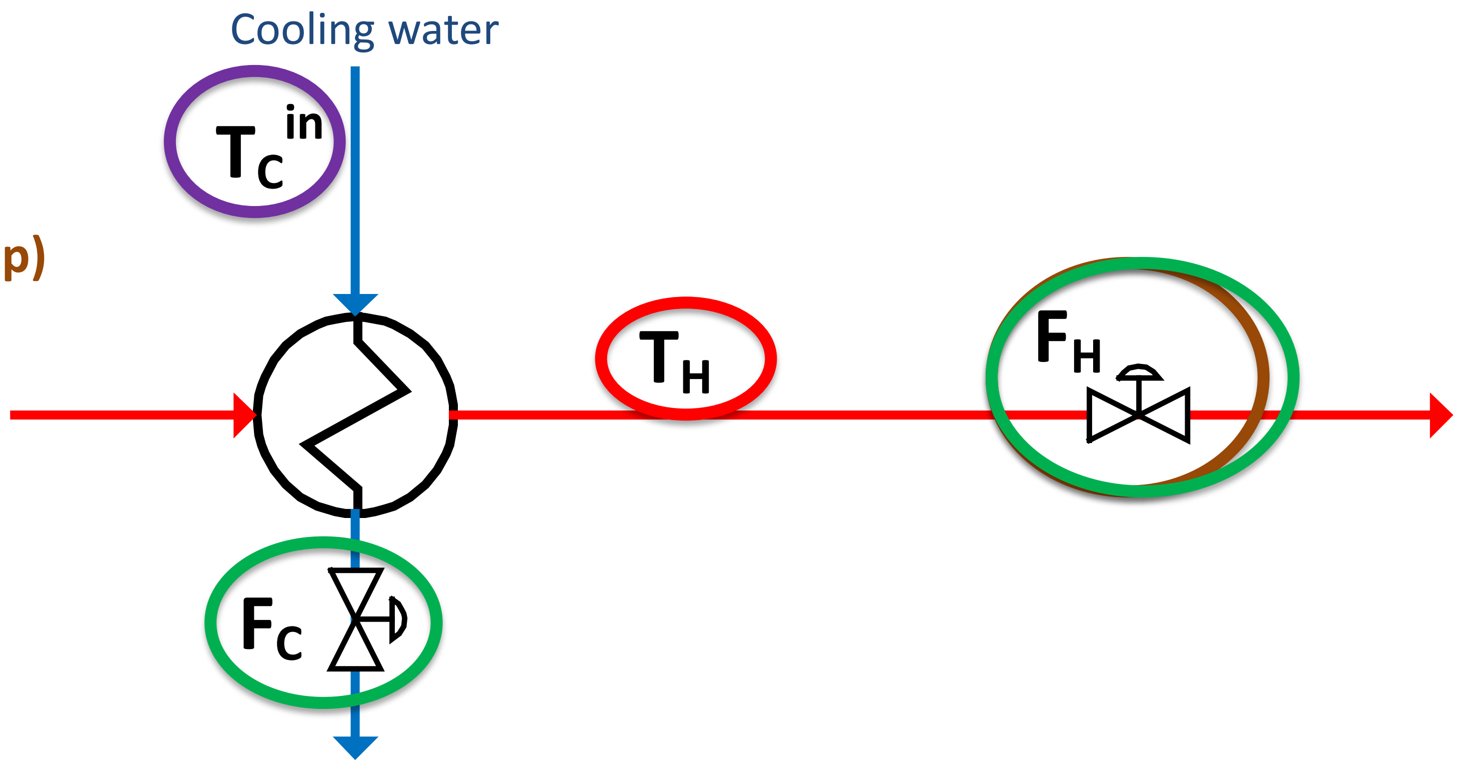
Manipulated Variables:

$u_1 = z_C$, $u_2 = z_H$

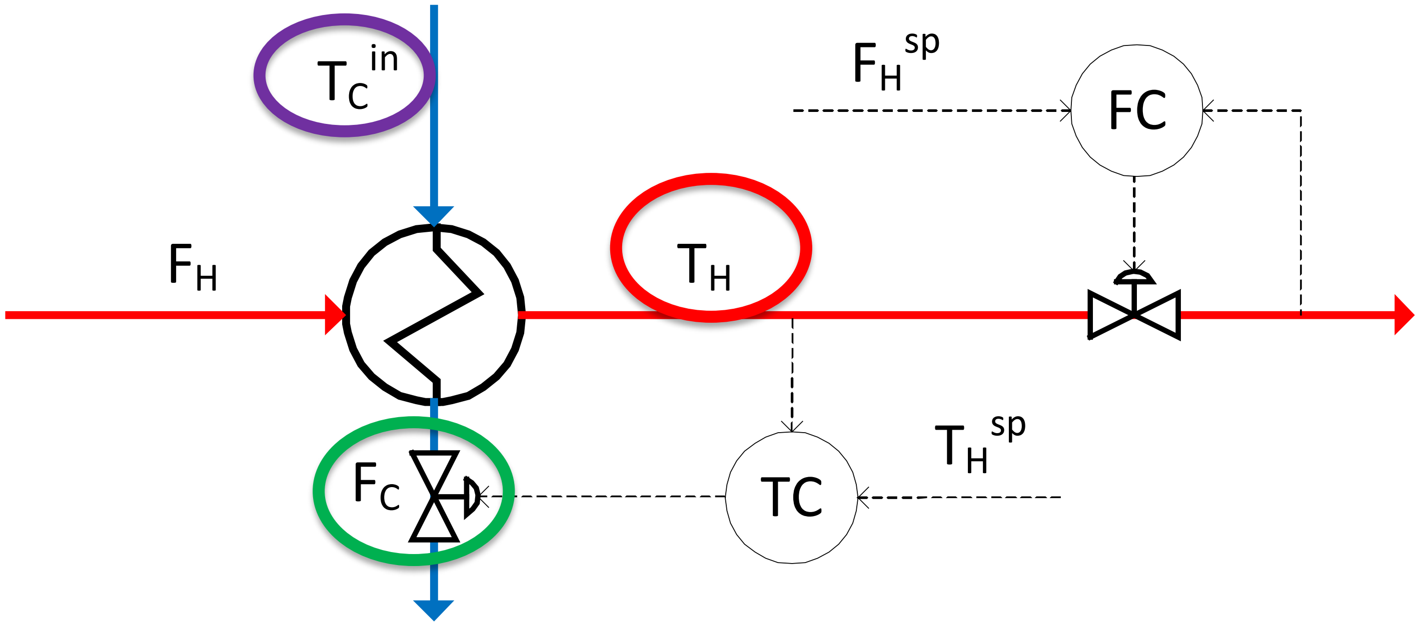
Both valves may satúrate at max

Disturbance:

T_C^{in}

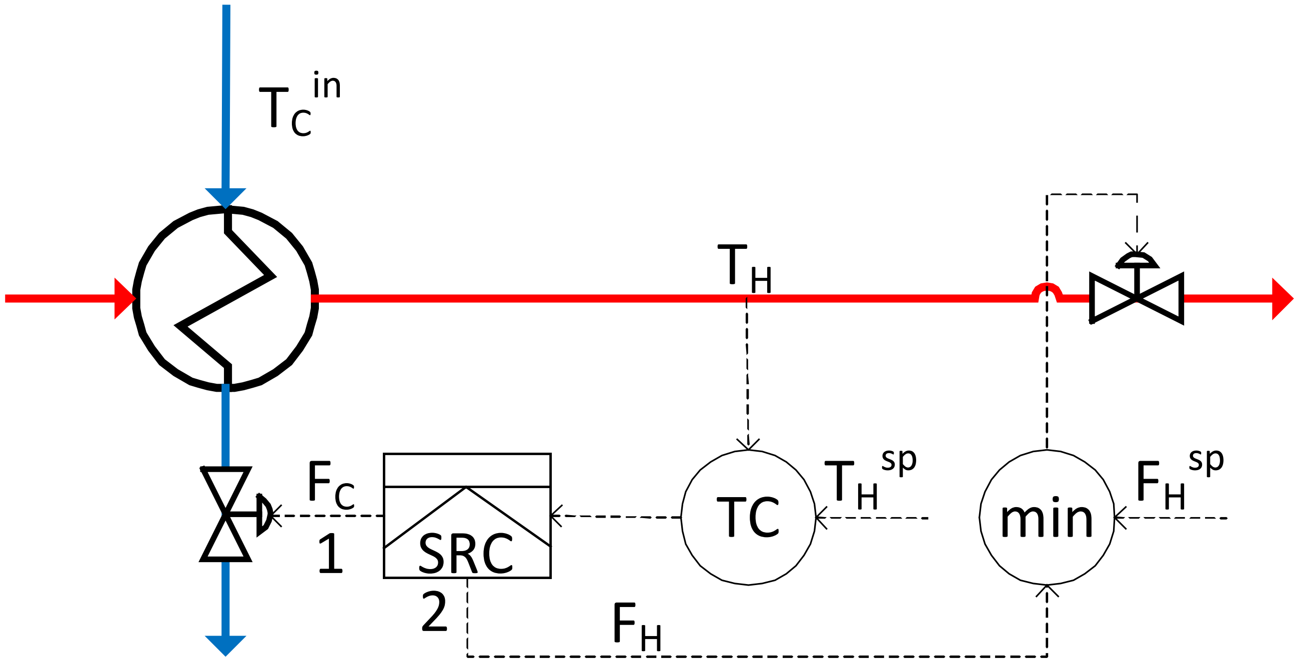


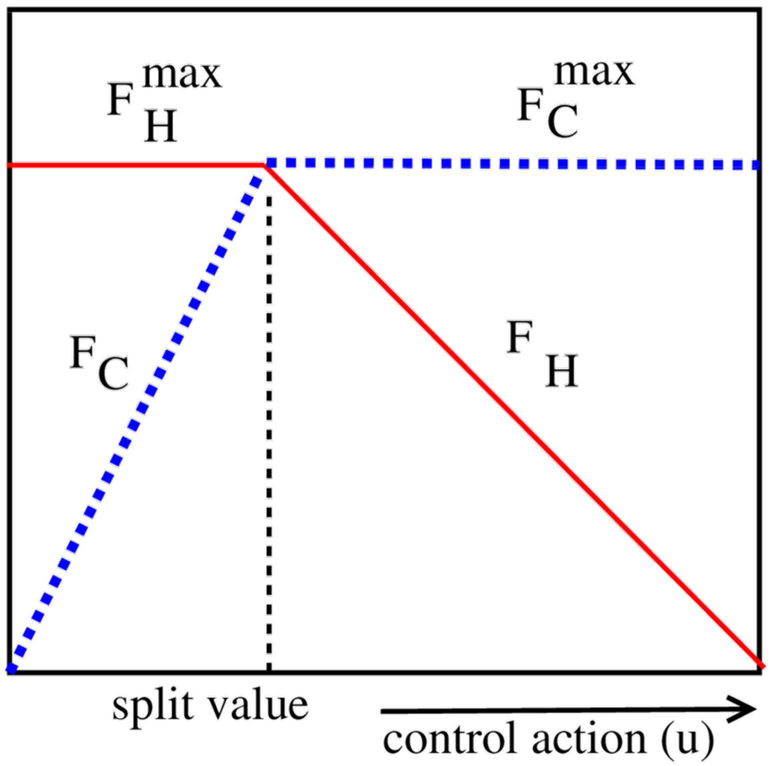
Pairings at nominal «unconstrained» operating point



Use F_C to control T_H → F_C may saturate for a large disturbance (T_C^{in})

Alt.1: Split range control with min-selector





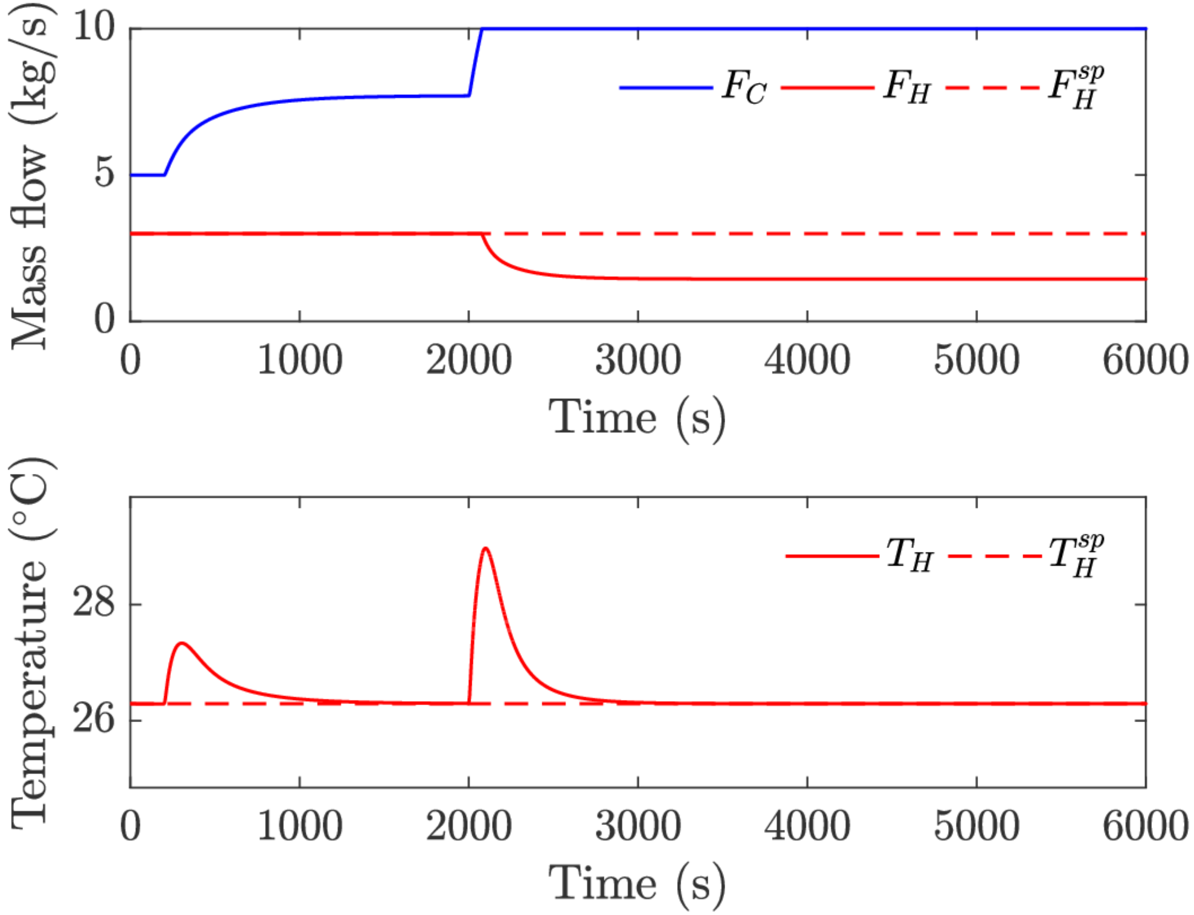
Tuning of TC using SIMC rule:

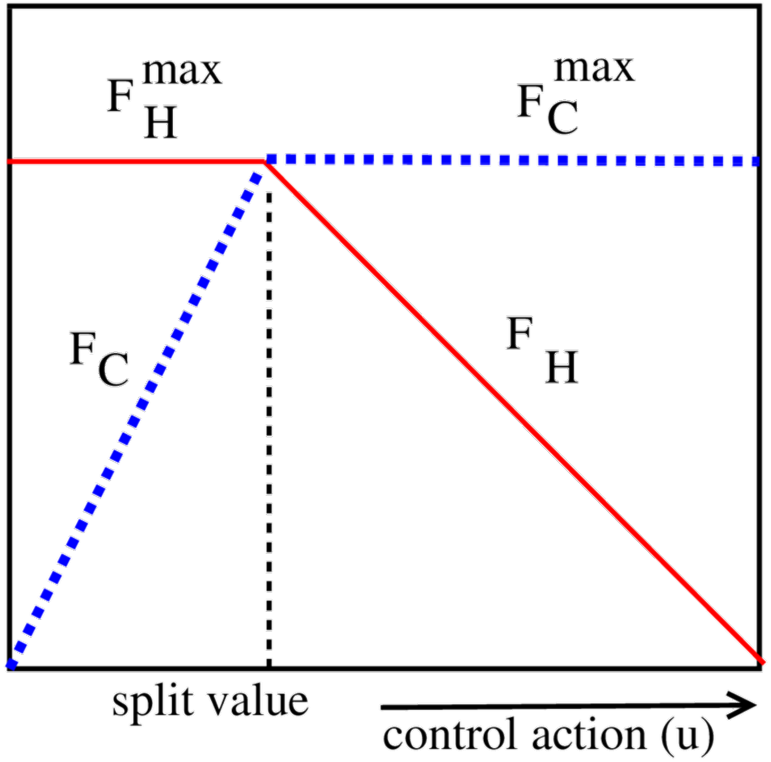
τ_c = 2θ = 88 s

Kc = -0.55

τ_I = 74 s

Simulation: Split range control with min-selector





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MPC for cooler

Tuning ← trial and error

$$\min \sum_{k=1}^{N} \left(\omega_1 \| (T_{H_k} - T_H^{sp}) \|^2 + \omega_2 \| (F_{H_k}^{max} - F_{H_k}) \|^2 \right)$$

← Objective function (CV constraints)

s.t.

Model →

MV constraints →

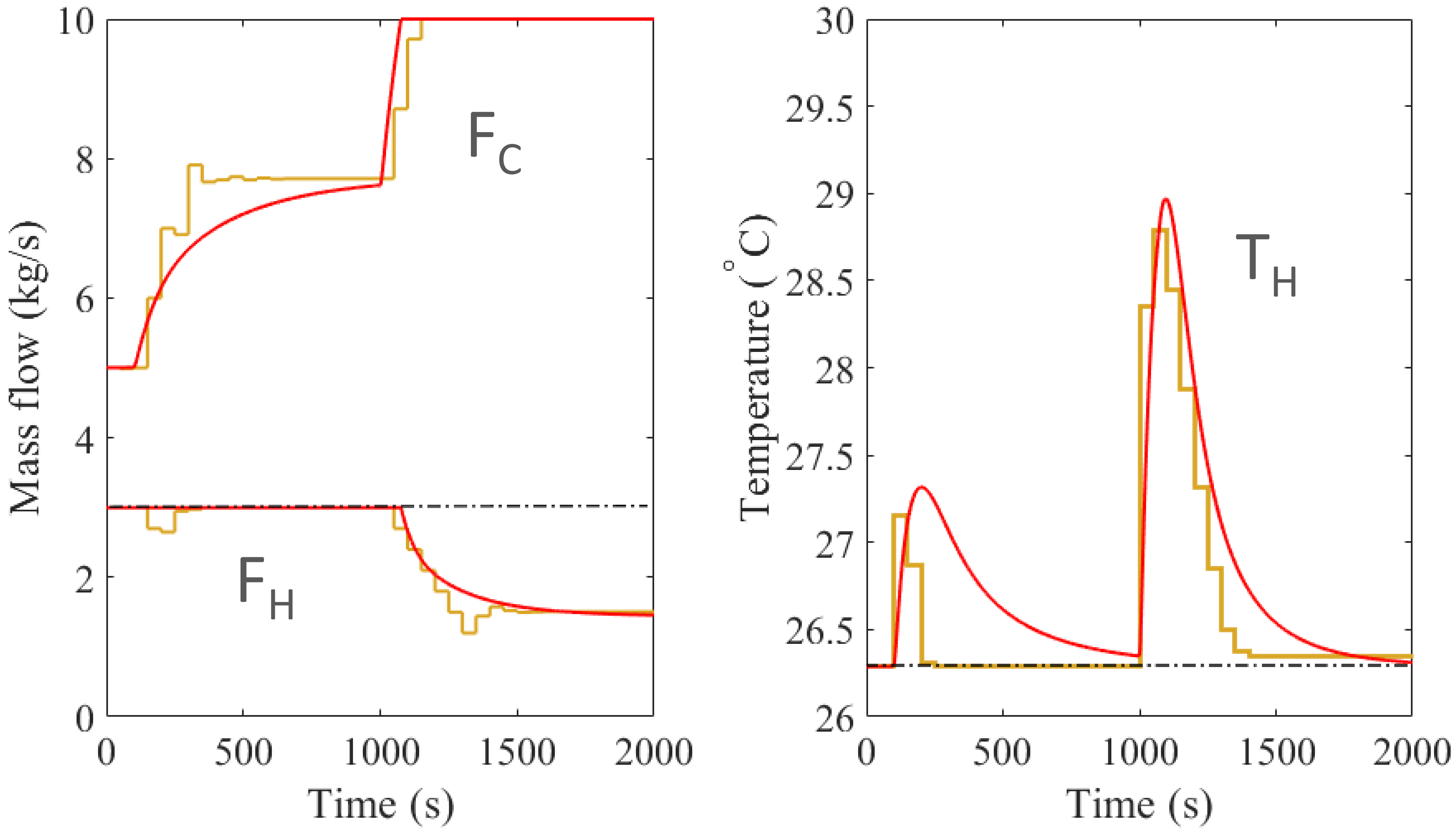
$$\left.\begin{aligned} & T_{k,i} = f(T_{H_k,i}, T_{H_k,i-1}, T_{C_k,i}, T_{C_k,i+1}, F_{H_k}, F_{C_k}) \\ & 0 \le F_{H_k} \le F_H^{max} \\ & 0 \le F_{C_k} \le F_C^{max} \end{aligned}\right\} \quad \forall k \in \{1, \ldots, N\}$$

$$\left.\begin{aligned} & 0 \le \Delta F_{H_k} \le 0.1 F_H^{max} \\ & 0 \le \Delta F_{C_k} \le 0.1 F_C^{max} \end{aligned}\right\} \quad \forall k \in \{1, \ldots, N-1\}$$

$$\Delta F_k = F_k - F_{k-1}, \forall k \in \{1, \ldots, N-1\}.$$

For $k = 1$, F_{k-1} represents the flow at the nominal point.

MPC vs PI



Disturbance
(T_C^{in})

t = 10 s; + 2°C

t = 1000 s; + 4°C

Red: Split Range Control (PI)

Yellow: MPC:

Δt = 50 s

$\omega_1 = 3$

$\omega_2 = 0.1$

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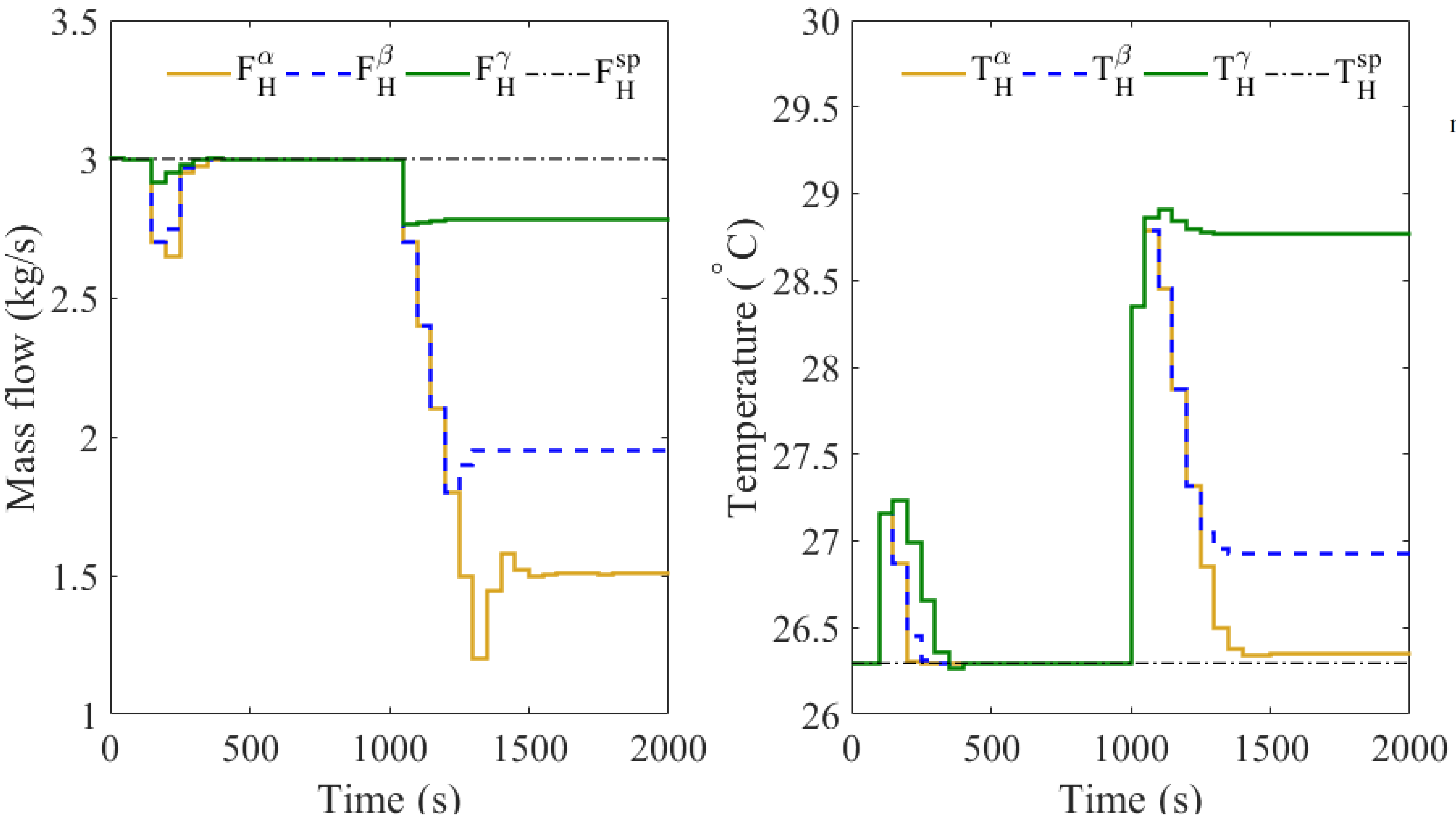
MPC weight selection



$$\min \sum_{k=1}^{N} \left(\omega_1 \left\| \left(T_{H_k} - T_H^{sp}\right) \right\|^2 + \omega_2 \left\| \left(F_{H_k}^{max} - F_{H_k}\right) \right\|^2 \right)$$

Tunings:
[ω₁ , ω₂]

α = [3.0, 0.1]

Yellow: Selected

β = [1.0, 1.0]

γ = [0.1, 3.0]

NTNU

4. Conclusion

- Optimal steady-state operation is achieved by controlling changing active constraints
- For most systems we can use PI-control + standard Advanced Process Control elements
  - MV-MV switching: Split range controllers or different setpoints
  - CV-CV switching: Max/min-selectors
  - CV-MV swithing: Nothing or combine MV-MV and CV-CV
- Comparison with MPC
  - Comparable response to MPC
  - Much less modeling efforts
  - Simpler implementation
  - More explicit constraint control
  - MPC preferable for more complex interactive processes